Joint EASE–EERA Recommendations for a

EUROPEAN ENERGY STORAGE TECHNOLOGY DEVELOPMENT ROADMAP TOWARDS 2030 – UPDATE
The European Association for Storage of Energy (EASE) is the voice of the energy storage community, actively promoting the use of energy storage in Europe and worldwide. Since its establishment in 2011, EASE has supported the deployment of energy storage as an indispensable instrument to support Europe’s ambitious clean energy and climate policies. EASE’s members come from all sectors of the energy storage value chain who are committed to supporting the transition towards a sustainable, flexible, and stable energy system in Europe.

For further information, please visit www.ease-storage.eu.

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**Contributing authors:** Myriam Elisa Gil Bardajií (KIT; EERA JP Energy Storage); Dan Bauer (DLR); Thomas Bauer (DLR); Brittney Becker (EASE); Laurent Bedel (CEA); Christian Bergins (MHPSE); Robert Bubeck (Bosch); Torsten Buddenberg (MHPSE); Mark Byrne (Gaelectric); Patrick Clerens (EASE), Giorgio Crugnola (FIAMM); Giovanna Cavazzini (U Padova); Mario Conte (ENEA); Yulong Ding (U Birmingham); Raymond Dorney (Gaelectric); Jean-Michel Durand (EASE); Jan Ernst (Maxwell Technologies); Maximilian Fichtner (KIT HII); Edouard de Frescheville (GE); Victoria Gerus (EASE); Duncan Gibb (DLR); Adelbert Goede (DIFFER); Fedor Gömöry (IEE SAS); Xavier Granados (CSIC); Peter Hall (U Sheffield); Atle Harby (SINTEF); Joris Koornneef (TNO); Marcos Lafoz (CIEMAT); Michael Lippert (Saft); Marc Linder (DLR); Cristina Luengo (CIC Energigune); Francesco Lufrano (CNR); Rowena McCappin (GlenDimplex); Kim McGrath (Maxwell Technologies); Fernando Morales (Highview Power); Lionel Nadau (ENGIE); Mathias Noe (KIT; EERA JP Energy Storage); Jesús Palma (IMDEA); Xiaodong Peng (U Birmingham); Joao Murta Pina (FCT UNL); Allan Schrøder Pedersen (DTU); Adriano Sciacovelli (U Birmingham); Edel Sheridan (SINTEF); Denis Thomas (Hydrogenics); Andrea Vecchi (U Birmingham); Jihong Wang (U Warwick); Antje Wörner (DLR); Stefan Zunft, DLR

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# Table of Contents

1. **Summary** .................................................................................................................. 6
2. **Methodology and Overview** ................................................................................... 8
3. **Mission and Objectives of the Roadmap** ............................................................. 10
4. **European and Global Policy as a Driver for Energy Storage Demand** .......... 11
   4.1 The Policy Framework ......................................................................................... 11
   4.2 Perspectives for the Future Energy System in Europe .................................... 13
   4.3 Role of Energy Storage ....................................................................................... 13
   4.4 Industrial opportunities for European Energy Storage ..................................... 14
   4.5 Conclusions ........................................................................................................ 15
5. **The Need for Energy Storage, Applications, and Potentials in Europe** ........ 16
   5.1 The Need for Energy Storage ............................................................................... 16
   5.2 Energy Storage Applications – Electricity Sector ............................................. 17
   5.3 Energy Storage Applications – Sector Coupling .............................................. 23
   5.4 Introduction to Energy Storage Technologies .................................................. 23
   5.5 European Competences in Energy Storage ...................................................... 25
6. **Energy Storage Technologies** ............................................................................... 33
   6.1 Chemical Energy Storage .................................................................................... 33
   6.2 Electrochemical Energy Storage ......................................................................... 40
   6.3 Electrical Energy Storage .................................................................................... 51
      Supercapacitors ...................................................................................................... 51
      Superconducting Magnetic Energy Storage (SMES) ............................................. 56
   6.4 Mechanical Energy Storage .................................................................................. 63
      Compressed Air Energy Storage .......................................................................... 63
      Flywheel Energy Storage ..................................................................................... 69
      Liquid Air Energy Storage ................................................................................... 73
      Pumped Hydro Storage ....................................................................................... 79
   6.5 Thermal Energy Storage ....................................................................................... 86
      Sensible Heat Storage ........................................................................................... 87
      Latent Heat Storage .............................................................................................. 94
      Thermochemical Heat Storage .......................................................................... 98
7. Market Design and Policy Recommendations....................................................... 103
   7.1 Policy Recommendations .............................................................................. 103
   7.2 Conclusions .................................................................................................. 106
8. Recommendations and Proposed Timeline for Activities................................. 108
   8.1 Identification of Energy Storage R&D Priorities ......................................... 108
   8.2 Recommendations and Timeline .................................................................. 109
1. Summary

The first joint EASE/EERA technology development roadmap on energy storage\(^1\) was published in 2013 with the goal of identifying the most pressing technology development priorities for the European energy storage industry. Given the many technological developments in the energy storage sector – and, indeed, the energy sector as a whole – over the past several years, EASE and EERA have joined forces once more to draft a significant update to the 2013 roadmap.

The roadmap is a joint effort between the European Association for Storage of Energy (EASE) and the Joint Programme on Energy Storage (JP ES) under the European Energy Research Alliance (EERA). The bulk of the work was completed between July and December 2016 by a core working group composed of EASE and EERA members, with coordination and support from the EASE and EERA JP ES secretariats. Together, EASE and EERA members provide a strong foundation of industrial and research expertise, which allows for a deep and multifaceted insight into the European energy storage sector.

This updated roadmap provides a comprehensive overview of the energy storage technologies being developed in Europe today, with a stronger focus on applications, and identifies the RD&D needs for energy storage in the coming decades. On this basis, the roadmap provides recommendations for R&D policies and regulatory changes needed to support the development and large-scale deployment of energy storage technologies. The aim is to inform policymaking for research, innovation, and demonstration in the energy storage sector in order to further strengthen Europe’s research and industrial competitiveness in the energy storage industry.

More information about the methodology used to elaborate this roadmap is contained in chapter 2. Chapter 3 lists the mission and objectives of this effort. Chapter 4 explains the European and global policy developments affecting the energy system in Europe and the role foreseen for energy storage. Chapter 5 describes the future needs for energy storage, explains the key energy storage applications for the electrical system and for sector coupling, provides an overview of the energy storage technologies, and outlines the European competences in energy storage.

EASE and EERA consider that a wide range of energy storage technologies will be needed to address the challenges of the energy transition. Chapter 6, the bulk of this roadmap, therefore covers the five families of energy storage technologies in detail: chemical energy storage, electrochemical energy storage, electrical energy storage (including both supercapacitors and superconducting magnetic energy storage), mechanical energy storage (covering compressed air energy storage, flywheels, liquid

air energy storage, and pumped hydro storage), and thermal energy storage (broken down into sensible heat storage, latent heat storage, and thermochemical heat storage). For each of these technologies, there is a description of its technical maturity, applications, R&D targets, an identification of gaps between the present status and these targets, a list of research priorities, and recommendations for research funding, infrastructures, and incentives.

Chapter 7 provides market design and policy recommendations aimed at reducing the barriers to energy storage deployment in Europe. This is important since ambitious R&D policy and funding alone will not be enough to achieve the energy storage capacity needed to support the EU’s decarbonisation goals.

In chapter 8, we summarise the R&D priorities we consider most pressing for the industry as a whole. We situate these along a rough timeline, based on an assessment of the most immediate needs and of which efforts are likely to yield the most promising returns for the energy system.
2. Methodology and Overview

The first joint EASE/EERA technology development roadmap on energy storage\(^2\) (ES) was published in 2013 with the goal of describing Europe's future needs for energy storage (by 2020–2030). The roadmap also contained recommendations on which technological developments would be required to meet those needs.

Since 2013, there have been significant developments in energy storage technologies, such as the installation of the world’s largest Liquid Air Energy Storage (LAES) demonstration plant in the UK\(^3\), the construction of Europe’s first hybrid flywheel plant in Ireland\(^4\), and the rapidly declining costs of batteries\(^5\) to name a few. Moreover, there have been significant changes in the market and regulatory framework. In response to these important developments, an update of the roadmap and recommendations was needed to adjust and redefine long-term storage targets (with a timeframe of 2030–2050 in mind).

The vast majority of reports describing future scenarios of the European energy landscape agree that energy storage will be one of the main tools to support the energy transition. They are often supported by quantitative modelling work assessing the generation profile of a society powered (almost) entirely by renewable energy sources (RES). The quantitative analyses unambiguously point to a significant future need for energy storage capacity in Europe, the size of which will naturally depend on many aspects of the energy system such as penetration of RES, electricity transmission capacity across Europe, penetration of demand-side management and alternative back-up power availability (e.g. biomass or acceptance of limited use of fossils in short time intervals).

Given this clear demand for energy storage capacity and services to respond to the challenges of an RES-dominated energy system, there is also a need to identify the energy storage technologies with the most promising potential for economic and technical development over the next 10 to 30 years. In this roadmap, the members of EASE and EERA’s Joint Programme Energy Storage (EERA JP ES) have sought to


\(^5\) Prices for Li–ion batteries have declined by more than 50% since 2010, according to Moody’s Investor Service: *Declining battery prices could lead to commercial and industrial customer adoption in 3–5 years*, 24 September 2015. [https://www.moodys.com/research/Moodys-Declining-battery-prices-could-lead-to-commercial-and-industrial---PR_335274](https://www.moodys.com/research/Moodys-Declining-battery-prices-could-lead-to-commercial-and-industrial---PR_335274)
identify these technologies based on their significant industrial and research expertise. In identifying the most promising storage technologies, the present state of European competences in industry and research has been taken into account as well as knowledge and assessments of the future requirements in Europe.

The roadmap recommendations have been prepared in close collaboration between EASE and EERA JP ES. For practical reasons the bulk of the roadmap was drafted by a joint core working group made up of representatives from both organisations. EASE members from all technology “families” came forward to contribute their expertise. From EERA, the subprogramme leaders and other members attended the working group. Finally all EASE and EERA members had the opportunity to comment on the document and make suggestions for corrections. Thus, the present document reflects the consolidated opinions and viewpoints of EASE and EERA members.

In addition, both EASE and EERA have drawn on broad stakeholder participation, as we consider this fundamental to the roadmap’s success. Following the principles of transparency and openness, we invited a group of relevant stakeholders to contribute to this joint EASE/EERA roadmap. The stakeholders had different possibilities to provide feedback along the process: by sending written comments on the first draft and by discussing this input in more detail during a stakeholder’s workshop organised by EASE and EERA.

The final document gives a short introduction to the topics of relevance as well as a brief description of the mission and objectives of the roadmap. The energy storage technologies are divided according to their families, allowing for a thorough focus on each area. Since technological development will not be the only driver for market uptake, each of these sections includes potential applications as well as the most obvious market opportunities. For each family of technologies, current performance is contrasted with targets for the coming 10–30 years. These targets are based on those listed in the SET-Plan Materials Roadmap on Enabling Low Carbon Energy Technologies6. However, since that Roadmap stems from 2011, in many cases the targets have been updated to reflect technological developments.

Lastly, the roadmap gives recommendations – both for the market design/EU policies and for R&D activities – to make the required developments become a reality. The recommendations address all relevant stakeholders, from European industry and researchers to European policymakers.

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3. Mission and Objectives of the Roadmap

The purpose of this Energy Storage Technology Development Roadmap is to:

- Provide recommendations for research, development and demonstration (RD&D) actions on energy storage for the Horizon 2020 and post-Horizon 2020 research frameworks, in line with the Energy Union goals. These actions will support the integration of RES in Europe while at the same time supporting the continued growth and competitiveness of the European energy storage industry.

- Present an overview covering the most discussed energy storage technologies, including their applications and research needs, based on the joint views of industry and research centres.

- Identify critical needs for each energy storage technology and/or technology gaps that must be filled to meet technology performance and cost targets.

- Set up milestones for the development of energy storage technologies over the coming 10–20 year period.

- Establish a dialogue at European level among all stakeholders involved in energy storage research and development (R&D) and provide a framework to plan and coordinate technology developments within the broader European energy storage community.

- Identify ways to leverage R&D investments through coordination of research activities.

- Advise policy makers by identifying regulatory hurdles and market failures hampering the business case for energy storage.
4. European and Global Policy as a Driver for Energy Storage Demand

For many years, energy storage was not considered a priority for the energy system, in part because the technologies were not yet economically viable and in part because the benefits of storage were valued less in a centralised fossil fuel-based energy system. However, this situation is rapidly changing due to the cost-performance improvements in energy storage technology and the public policy commitment to decarbonisation, leading to a significant increase in RES as a share of electricity generation. This chapter outlines the developing energy and climate policy framework of the European Union (EU) and how it is a driver of demand for energy storage with the integration of RES and the transition to a low-carbon energy system.

4.1 The Policy Framework

The EU’s energy and climate policies have become increasingly ambitious over the years. Since the Climate and Energy Package, with its ‘20–20–20’ targets\(^7\), was agreed in 2007, the EU has issued a host of strategies and policies to support the development of a low-carbon energy system.

In October 2014, EU Member States agreed on ambitious EU-wide climate and energy targets for 2030: a 40% cut in greenhouse gas emissions compared to 1990 levels; at least a 27% share of renewable energy consumption; and at least 27% energy savings compared with the business-as-usual scenario. The Paris Agreement\(^8\), which was approved at the Conferences of the Parties (COP21) in December 2015 and became legally binding in November 2016 following its ratification, requires the EU to further strengthen its 2030 energy and climate framework through legislative action. It also steers the entire global community on a path to decarbonisation, which will increase the global need for low-carbon energy generation and therefore also for low-carbon balancing and flexibility means.

The energy sector is at the heart of discussions about addressing the threat of climate change, which is why EU policymakers closely link climate and energy policies. In February 2015, the European Commission proposed the Energy Union strategy, whose main goal is to ensure a secure, sustainable, competitive, and affordable energy supply in Europe. The EU integrates different policies areas – energy security,

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internal energy market, energy efficiency, decarbonisation of the economy, and research, innovation and competitiveness – into one cohesive strategy. To implement the goals of the Energy Union and to advance the energy transition, the EU issued the “Clean Energy for all Europeans” package in November 2016. This includes several key pieces of legislation: the important amendments to the Third Energy Package known as Energy Market Design; the Accelerating Clean Energy Innovation communication; the new Renewable Energy Directive; the Directive on the EU Emissions Trading System; and the Directive on Energy Efficiency.

Energy research and innovation also play an important role in the EU’s strategy to transition to a low–carbon energy system. The 2015 Energy Union Communication stated that the EU “is committed to becoming the world leader in renewable energy, the global hub for developing the next generation of technically advanced and competitive renewable energies”\(^\text{10}\). One pillar of the Energy Union is the Strategic Energy Technology Plan (SET–Plan), which focuses on accelerating the development and deployment of technologies with the greatest impact on the decarbonisation of the energy system. The implementation of Horizon 2020, the €80 billion EU Framework Programme for Research and Innovation, will also contribute to the objectives of the Energy Union.

The communication on Accelerating Clean Energy Innovation identifies “Developing affordable and integrated energy storage solutions” as one of four priority R&I areas.\(^\text{11}\) In this communication, the Commission also announces that it intends to deploy more than €2 billion from the Horizon 2020 work programme for 2018–2020 to support research and innovation projects in these four priority areas.\(^\text{12}\) This represents a 35% budget increase in annual terms from 2014–2015 levels in these areas. This financial support, guided by clear strategic objectives, will play a significant role in accelerating the development of the secure, clean and efficient energy technologies necessary to achieve the EU’s decarbonisation goals.


\(^{11}\) European Commission: Communication on Accelerating Clean Energy Innovation, 2016. \url{http://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v6_0.pdf}

\(^{12}\) The priority areas are: (1) Decarbonising the EU building stock by 2050: from nearly–zero energy buildings to energy–plus districts; (2) Strengthening EU leadership on renewables (RES); (3) Developing affordable and integrated energy storage solutions; and (4) Electro–mobility and a more integrated urban transport system.
4.2 Perspectives for the Future Energy System in Europe

Driven by the above policies, significant changes are expected in the European energy system by 2050. According to the International Energy Agency (IEA), the increasing electrification of many sectors, such as transport and heating and cooling, means that the globally installed capacity would have to more than double by 2040. Electricity demand is expected to rise by more than a third by 2050 compared to 2000 levels. Meanwhile, in the EU, the share of RES in electricity generation is expected to reach 24% in 2030 and 56% by 2050. Achieving a significant level of decarbonisation already in 2030 will require the power generation system to undergo significant structural changes. There will be a fundamental shift from a centralised energy system based on fossil fuels to a distributed generation system supported by a range of flexibility options. In a system with a high proportion of variable RES generation, it will be challenging to ensure that electricity supply and demand are balanced across time and space. In addition, voltages and frequency of grid electricity will have to remain within required ranges.

The implementation of these changes necessitates significant investments for the development and large-scale deployment of low-carbon energy technologies. The European Commission estimates that cumulative grid investments costs alone could amount to between €1.5 and €2.2 trillion between 2011 and 2050, with the higher range corresponding to greater investment in RES. This investment is not only required for RES but also for the technologies that can support an increased share of RES in the system, including energy storage, interconnections, and smart grids.

4.3 Role of Energy Storage

Alongside other flexibility options, energy storage will play a crucial role in the transition to a low-carbon energy system. The IEA estimates that limiting global warming to below 2°C will necessitate globally installed energy storage capacity to increase from 140 GW in 2014 to 450 GW in 2050. This threefold increase is necessary because, as the European Commission underlines, “energy storage can support the EU’s plans for Energy Union by helping to ensure energy security, a well-functioning internal market and helping to bring more carbon-cutting renewables...”

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online. By using more energy storage, the EU can decrease its energy imports, improve the efficiency of the energy system and keep prices low by better integrating variable renewable energy sources. Chapter 6 of this roadmap provides further details about the full range of applications and services that can be met by energy storage and are driving its demand.

Although the European Commission and European Parliament recognise the importance of energy storage, the regulatory framework has not yet evolved to support the cost-efficient deployment of energy storage. For instance, the lack of a definition of energy storage at EU level leads to uncertainty about how energy storage devices should be treated under current regulations. Fortunately, this issue is addressed in the recast Electricity Directive issued by the Commission in November 2016. Onerous requirements in the network codes also constitute barriers to energy storage deployment. These barriers, as well as suggested policy recommendations to address them, will be discussed in more detail in chapter 8.

4.4 Industrial opportunities for European Energy Storage

Energy storage will clearly play an increasingly vital role in a decarbonised global energy system, as CO$_2$-free balancing and flexibility means are a prerequisite for a decarbonised future. Also, the EU's costly dependence on fossil fuel imports – the EU currently imports 53% of all the energy it consumes at a cost of more than €1 billion per day – provides a clear incentive to increase generation on the basis of (variable) indigenous energy resources in Europe.

This means that the energy storage market will see rapid expansion in the next years and decades: the global market is forecast to grow to at least $250 billion by 2040. With this massive growth comes a unique opportunity for the European energy

storage industry to ramp up the production of technologies and provision of associated services in Europe and abroad. In doing so, the energy storage industry could contribute to re-industrialising Europe, contributing to long-term growth for European citizens while supporting the EU’s ambition to make Europe the world number one in renewables.

However, achieving this industrial growth will require support from policy makers, on par with efforts being made by governments of other countries. For some energy storage technologies, European industry has a strong leadership position. For others, European companies are competing fiercely for global market share. Chapter 5.4 provides a more detailed picture of European Competences in Energy Storage. Only a courageous level of political support for research, development and demonstration in the promising energy storage will allow European industry to play a leading role on global markets.

4.5 Conclusions

Energy storage already plays an important role in the energy system. The EU’s pursuit of ambitious climate and energy policies, as well as global climate agreements, will drastically increase the need for effective energy storage technologies. This presents a promising opportunity for European companies, but a challenge for policy makers. The rapid development and deployment of energy storage technologies and applications must be supported through ambitious RD&D programmes coupled with regulatory change and an ambitious industrial policy.
5. The Need for Energy Storage, Applications, and Potentials in Europe

5.1 The Need for Energy Storage

A massive increase in renewable energy generation and expanding electric vehicle networks are accelerating the need for efficient, reliable, and economical energy storage solutions.

An increased demand for energy storage will also be driven by the following factors:

- There will be a **significant increase in variable renewable energy** in Europe and all around the world. Energy storage will provide an effective solution to bridge fluctuations at different time–scales in supply and demand.

- In recent years, we already observe a **considerable increase in renewable energy curtailment**. Energy storage could strongly reduce this level of curtailment, thereby reducing carbon dioxide (CO₂) emissions, decreasing import dependency on fossil fuels, and improving the return on renewable energy generation investments.

- There is a need to further **increase energy efficiency and to reduce CO₂ emissions**. Energy storage will, for example, contribute to a higher efficiency for energy-intensive industrial processes and more flexibility for conventional power plants.

- In an energy system based on renewable energy, there is a need for **improved links between different energy carriers** (e.g. electricity, gaseous fuels, liquid fuels, and heat) to absorb surplus electricity generation and decarbonise sectors that are still heavily reliant on fossil fuels. Energy storage provides an effective means to establish effective links between different energy carriers.

In 2015, installed large-scale energy storage capacity world-wide was estimated at 150 GW with approximately 96% of this capacity consisting of pumped hydro storage (PHS). More than 70% of new installations completed in 2014 are still PHS. The development of worldwide installed energy storage capacity in recent years is shown in Figure 1. It shows that thermal energy storage, large-scale batteries, flywheels,

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and compressed air energy storage (CAES) are the main components of the non-PHS energy storage capacity.

Figure 1: Worldwide installed energy storage capacity

Several forecasts\textsuperscript{24,25,26} predict that in most key markets the overall installations and market for energy storage will increase significantly in the coming years. For example, in the United States a nine-fold growth of the market over the next five years across all segments of energy storage is expected\textsuperscript{27}, which would result in 2 GW of new installations by 2021.

5.2 Energy Storage Applications – Electricity Sector

Figure 2 shows that, in addition to RES integration and arbitrage, there is a wide range of potential energy storage applications at all levels ranging from energy generation, transmission, and distribution up to the customer or load site. Each application is described below.

\textsuperscript{23} IEA: Energy Snapshot of the Week, 2015. \url{https://www.iea.org/newsroomandevents/graphics/2015-06-30-installed-global-capacity-for-grid-connected-storage.html}


\textsuperscript{25} International Energy Agency: World Energy Outlook 2016. \url{www.iea.org}

\textsuperscript{26} Navigant Research: Market Data: Commercial & Industrial Energy Storage, Q1 2016. \url{https://www.navigantresearch.com/research/market-data-commercial-industrial-energy-storage}

<table>
<thead>
<tr>
<th>Generation/Bulk Services</th>
<th>Ancillary Services</th>
<th>Transmission Infrastructure Services</th>
<th>Distribution Infrastructure Services</th>
<th>Customer Energy Management Services</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arbitrage</td>
<td>Primary frequency control</td>
<td>Transmission investment deferral</td>
<td>Capacity support</td>
<td>End-user peak shaving</td>
</tr>
<tr>
<td>Electric supply capacity</td>
<td>Secondary frequency control</td>
<td>Angular stability</td>
<td>Contingency grid support</td>
<td>Time-of-use energy cost management</td>
</tr>
<tr>
<td>Support to conventional generation</td>
<td>Tertiary frequency control</td>
<td>Transmission support</td>
<td>Distribution investment deferral</td>
<td>Particular requirements in power quality</td>
</tr>
<tr>
<td>Ancillary services RES support</td>
<td>Frequency stability of weak grids</td>
<td></td>
<td>Distribution power quality</td>
<td>Maximising self-production &amp; self-consumption of electricity</td>
</tr>
<tr>
<td>Capacity firming</td>
<td>Black start</td>
<td></td>
<td>Dynamic, local voltage control</td>
<td>Demand charge management</td>
</tr>
<tr>
<td>Curtailment minimisation</td>
<td>Voltage support</td>
<td></td>
<td>Intentional islanding</td>
<td>Continuity of energy supply</td>
</tr>
<tr>
<td>Limitation of upstream disturbances</td>
<td>New ancillary services</td>
<td></td>
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<td>EV integration</td>
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Figure 2: Overview of energy storage applications. Source: EASE

**Generation/Bulk Services**

- **Arbitrage** is the practice of taking advantage of an electricity price difference in the wholesale electricity market. It is the use of storage to buy energy at a low price and sell it at a higher price.

- **Electric supply capacity** is the use of energy storage in place of a combustion turbine to provide the system with peak generation capacity.

- **Support to conventional generation** is related to the optimisation of their operation:
  - Generator bridging: consists in the ability of energy storage systems (ESS) to pick up a generator load while the generator is stopping, until
a new generator starts up or the same generator is restarted. ESS can also avoid stopping the unit (and the associated starting costs) by charging in moments of low load.

- **Generator ramping:** consists in the ability of ESS to pick up strong and fast load variations, giving enough time for a given generator to ramp-up/-down its production level according to the optimal technical recommendations to meet load variation at stake.
- **Hedging imbalance:** charges due to deviations of final physical notifications.

- **Ancillary services RES support** is the use of energy storage to help intermittent renewable generation to contribute to ancillary services by keeping some reserve power, thus “wasting” a part of the down regulation of non-dispatchable RES.

- **Capacity firming** is the use of energy storage to make variable RES output more constant during a given period of time. Energy storage is used to store variable energy production (wind or solar) during hours of peak production regardless of demand. This energy is then discharged to supplement generation when the variable energy unexpectedly reduces its output. This application also includes RES smoothing, i.e. balancing short duration intermittency from wind generation caused by variation of wind speed and from photovoltaic (PV) generation due to shading caused by terrestrial obstructions such as clouds or trees.

- **Curtailment minimisation:** use of energy storage to absorb variable RES (wind or solar) that cannot be injected into the electricity grid and to either deliver it to the electricity grid when needed or convert it into another energy vector (gas, fuel or heat) to be delivered to the relevant grid.

- **Limitation of upstream disturbances:** energy storage is used to limit the disturbances caused by the distributed variable RES generators (wind or PV):
  - **Short duration:**
    - Reduce output volatility related to short-duration variation of wind or PV generation output, lasting seconds to a few minutes.
    - Improve power quality: reactive power, harmonics, voltage flicker, transmission line protection, transient stability, dynamic stability, and system voltage stability.
  - **Long duration:**
    - Reduce output variability related to natural wind speed variability over durations of several minutes to a few hours.
    - Transmission congestion relief.
    - Backup for unexpected wind/PV generation shortfall.
Ancillary Services

- **Reduce minimum load violations.**

**Ancillary Services**

- **Primary frequency control** has as its objective to maintain a balance between generation and consumption (demand) within the Synchronous Area. It aims to stabilise the system frequency at a stationary value after a disturbance or incident in the time-frame of seconds, but without restoring the system frequency and the power exchanges to their reference values. Traditionally, the providers of this service have 30 seconds to deploy to full power. Some energy storage technologies can be deployed within a fraction of a second.

- **Secondary frequency control** is a centralised automatic control that adjusts the active power production of the generating units to restore the frequency and the interchanges with other systems to their target values following an imbalance. While primary control limits and stops frequency excursions, secondary control brings the frequency back to its target value.

- **Tertiary frequency control** is used to restore the primary and secondary frequency control reserves, to manage congestions in the transmission network, and to bring the frequency and the interchanges back to their target value when the secondary frequency control is unable to perform this last task.

- **Frequency stability of weak grids** is a service that aims to maintain the frequency stability by helping avoid load shedding on islands due to the very prompt response of distributed energy storage systems.

- **Black start** is the use of energy storage to restore the system or a power plant after a black-out, as some electricity is needed which cannot be drawn from the grid.

- **Voltage support** serves to maintain voltage through injecting or absorbing reactive power by means of synchronous or static compensation. Different kinds of voltage control are implemented by individual TSOs, based on their own policies:
  - Primary voltage control is a local automatic control that maintains the voltage at a given bus at its set point.
  - Secondary voltage control is a centralised automatic control that coordinates the actions of local regulators in order to manage the injection of reactive power within a regional voltage zone.
  - Tertiary voltage control refers to the manual optimisation of the reactive power flows across the power system.

- **New ancillary services** dedicated to RES integration at high RES levels include synchronous inertia, ramping margin, fast frequency response, dynamic reactive response, etc.
Transmission

- *Transmission investment deferral* is the use of energy storage to defer any transmission infrastructure upgrade and so to solve transmission congestion issues.

- *Angular stability* refers to the use of energy storage to charge and discharge high levels of energy in short periods when an accident occurs.

- *Transmission support* is the use of energy storage to improve the performance of the transmission system by compensating for electrical anomalies and disturbances such as voltage sag, unstable voltage, and sub-synchronous resonance.

Distribution

- *Capacity support* is the use of an energy storage unit to shift load from peak to base load periods to reduce maximum currents flowing though constrained grid assets. This supports the integration of renewable electricity sources.

- *Contingency grid support* is the use of energy storage to support the grid capacity and voltage to reduce the impacts of the loss of a major grid component. Energy storage might also be useful in emergency situations, for example after the loss of a major component of the distribution grid.

- *Distribution investment deferral* is the use of energy storage to defer distribution infrastructure upgrades.

- *Distribution power quality* refers to the use of energy storage by the distribution system operator (DSO) to maintain the voltage profile within acceptable limits, which increases the quality of supply (less probability of black out or interruptions).

- *Dynamic local voltage control* aims to maintain the voltage profile within admissible contractual or regulatory limits. In distribution grids, voltage support can rely both on reactive power and active power modulations.

- *Intentional islanding* refers to of an intentional or unintentional islanding of a distribution grid, whereby energy storage can be used to improve system reliability by energising a feeder during an outage.

- *Limitation of upstream disturbances* relates to the fact that DSOs have a network access contract with one or more TSOs which requires them to limit the disturbances they cause on upstream high voltage grids to contractual values. If these limits are exceeded, some types of energy storage systems can help comply with these commitments by performing active filtering.
• **Reactive power compensation** is the contribution of energy storage to reactive power compensation by reducing the amount of reactive energy drawn from the transmission system and charged by the transmission system operator to the distribution system operator.

**Customer Energy Management Services**

• **End-user peak shaving** is the use of energy storage devices by customers such as industrials for peak shaving, or smoothing of own peak demand, to minimise the part of their invoice that varies according to their highest power demand.

• **Time-of-use energy cost management** is the use of energy storage to be charged when the rates are low and to be consumed during peak times, with the aim of reducing the invoice of final users.

• **Particular requirements in power quality** has as its objective to use energy storage to provide a high level of power quality above and beyond what the system offers (e.g. critical load) to some customers.

• **Maximising self-production & self-consumption** is the use of energy storage in markets with high energy costs to increase self-consumption in combination with a renewable energy source. A common example is the combination of batteries and photovoltaics.

• **Demand charge management** is the use of energy storage to reduce the overall customer costs for electric service by reducing demand charges during peak periods specified by the utility.

• **Continuity of energy supply** relates to the ability of an energy storage device to substitute the network in case of interruption, thereby reducing the damage for industry and households in case of blackout. These devices are often called uninterruptable power supply (UPS) units.

• **Limitation of upstream disturbances** is the use of energy storage for the limitation of disturbances transmitted at upper levels.

• **Compensation of the reactive power** refers to the ability of energy storage devices connected via a power electronics converter to locally compensate the reactive power and thereby influence mainly voltage.

• **Electric Vehicles (EV) Integration** is the use of EVs or plug-in hybrid electric vehicles (PHEV) to provide vehicle to grid (V2G) functions to contribute to grid balancing.
5.3 Energy Storage Applications – Sector Coupling

In addition to the electrical applications outlined above, energy storage is able to provide additional services to the energy system that can loosely be grouped under the “sector coupling” heading. These are services that can help provide competitive flexibility to the EU electricity system by integrating the electricity, heating & cooling, and transport sectors.

These applications include:

- **Large-scale, long-term (weekly, monthly or seasonal) energy storage of renewable electricity**, which can be provided by chemical energy storage or thermal energy storage. Underground Thermal Energy Storage (UTES), for example, can provide a solution for regions that have a clear seasonal dip and peak in heating demand, since it allows for the storage of surplus heat in the summertime for use in the winter.

- **Waste heat recovery** for power plants and industrial processes. In industrial processes, waste heat is often generated at completely different locations and temperature levels, which hampers the integration of this energy into the system. Thermal energy storage (TES) can solve the mismatch by recovering waste heat and storing it for a later use. This can lead to a decrease in CO₂ emissions as well as economic and energy savings²⁸.

5.4 Introduction to Energy Storage Technologies

Energy storage technologies are commonly classified according to their type, or family, as seen in Figure 3. There are five energy storage families. The members of a family may change in accordance with technological evolutions, but the five categories reflect the five storage principles. Therefore, the examples in each category should not be seen as an exhaustive list of potential family members.

---

**Chemical**
- **Hydrogen**
- **Synthetic Natural Gas**
- **Hydrocarbons**

**Electrochemical**
- **Classic Batteries**
  - Lead Acid
  - Li-Polymer
  - Metal Air
  - Na–NiCl₂
  - Ni-Cd

- **Flow Batteries**
  - Li-Ion
  - Li-S
  - Na–Ion
  - Na-S
  - Ni-MH

- **Vanadium Red-ox**
- **Zn–Br**

**Electrical**
- **Supercapacitors**
- **SMES**

**Mechanical**
- **Flywheels**
- **Adiabatic Compressed Air**
- **Pumped Hydro**
- **Diabatic Compressed Air**
- **Pumped Heat Electrical Storage**
- **Cryogenic Energy Storage**

**Thermal**
- **Sensible Heat Storage**
- **Latent Heat Storage**
- **Thermochemical Heat Storage**

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**Figure 3: Overview of different energy storage technologies**

- **Chemical energy storage** stores energy in chemicals that appear in gaseous, liquid or solid form and energy is released in chemical reactions. Major characteristics are a high energy density and a variety of transport and storage options.

- **Electrochemical energy storage** covers batteries, where chemical energy is stored and converted to electrical energy. There are many options that differ in electrode and electrolyte materials and as a result in their major parameters. There are two categories: classical batteries and flow batteries.

- **Electrical energy storage** stores electrons. In a capacitor, the electricity is stored in the electrostatic field between two electrodes. In superconducting magnetic energy storage (SMES), the electricity is stored in the magnetic field of a coil. The energy capacity is limited but the reaction time is fast, while the power and efficiency are very high.

- **Mechanical energy storage** combines several storage principles like the potential energy of water in hydro storage, the volume and pressure work of air in compressed air energy storage, the rotational energy of a mass in flywheels and the stored energy in cryogenic liquids.

- **Thermal energy storage** includes three types of technologies. There is storage in the sensible heat of materials, mainly defined by the heat capacity and the temperature difference. In latent heat storage the latent heat of phase change
of materials is used and thermochemical reactions are a further option for thermal energy storage.

A detailed explanation of each kind of energy storage is given in chapter 6.

5.5 European Competences in Energy Storage

Chemical Storage
Chemical storage is an area that has shown rapid development in Europe in recent years. Considerable funding from both the EU and Member States has created a vibrant research community in the production, storage, and conversion of hydrogen, which can be re-electrified via fuel cells. As with batteries, new innovative materials and devices have created a range of technological options for exploitation for industry. Many projects in power–to–gas are emerging in Germany and other European countries. Indeed, the majority of hydrogen storage projects worldwide are currently installed in Europe\(^29\). Most demonstration projects envisage the use of hydrogen for mobility purposes or wholesale via gas grid, but only a few of them include large–scale storage and electrification in their scope. Chemical storage is well suited to facilitate the integration of a large share of RES, which will play an increasingly important role in Europe. The European chemical storage industry is therefore expected to grow significantly.

Electrochemical Storage
The European industry’s position is strong in the most mature electrochemical storage technologies, such as Lead–Acid\(^30\) & Ni–Cd batteries. The situation is different for the Li–ion batteries segment, which is currently dominated by Asian actors (chiefly located in Japan, Korea, and China)\(^31\) because of its wide use in products such as mobile phones and portable computers. With the increasing use of Li–ion batteries in both automotive and grid applications, Europe will need to develop its own production capacity in this field. Li–ion batteries are excellent for both cyclability and weight, and are rapidly declining in cost. While many other chemistries are proposed as future options, continuous improvement of Li–ion batteries may be one of the main drivers for electrochemical energy storage for many years.


Some NaS battery projects have been set up in France, Germany and UK, although most of these projects are located in Japan and the United States. M–Air is considered as a valuable candidate to substitute the Li–Ion batteries in the upcoming 10–15 years because of expected developments in performance. Na–Ion batteries are also considered a possible successor for Li–ion batteries due to significant cost reductions expected in the coming years. Although it was first developed in the United States, Li–S technology is also considered as one of the applicants to replace Li–Ion in the upcoming 5–10 years in Europe, thanks to its larger energy density and the employment of low cost materials. Nonetheless, all of these materials will need significant improvements in cyclability before they will be viable candidates to compete with Li–ion. In the meantime, Li–ion will continue to improve in performance, supported by a huge market, making it more difficult for the competition.

Likewise, Na/NiCl₂ is mainly used in public transport and is manufactured in the EU (first) since 1999 and then in the United States. Finally, flow batteries are a mature technology: they have been produced since the early 1970s in the United States, then in Asia and Australia. In Europe, the research is chiefly focused on small devices and on developing cost–effective new membranes and increasing the power density of the cell. There are only a few companies worldwide offering redox flow batteries to the market, all of which are located in Europe.

The joint development of the European battery market for transport and stationary applications represents a big opportunity for strong industrial suppliers, supported by a strong European R&D network to be able to compete against the Asian industrials in a sector where European competences are rapidly increasing. Additionally, Europe is a leader in system integration of renewables and, increasingly, storage devices and further efforts are expected in the coming years.

### Electrical Storage

#### Ultracapacitors

The first discoveries in this field were made in 1957. Since the early 1980s niche uses have been seen and a broader deployment of Electrochemical Capacitors (ECs) has accelerated over the last 20 years. Ultracapacitors have been in commercial use for decades in both transportation and grid back up applications such as wind pitch control systems, demonstrating the lowest cost of ownership in high power/low energy and rapid cycling applications. Their long cycle life (~1 million cycles) and calendar life (10–25 years) coupled with a wide operating temperature range (−40–65°C) are well matched with existing grid assets. The deployment of ultracapacitors

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in grid energy storage systems – as a stand-alone energy storage technology or hybridised with batteries – is rapidly growing.

Future research and development activities are focused towards improving energy density of the core technology, and power electronics that support the control and management of ultracapacitors combined with batteries or another secondary storage technology. In Europe the main producers of ultracapacitors are based in Germany and France; however, the larger producers are located in Asian countries.

Superconducting Magnetic Energy Storage (SMES)

In recent years, several successful R&D projects on SMES have been carried out in Europe but there is currently no European commercial supplier of SMES. The main competences are within R&D institutes, which have successfully developed several demonstrators and prototypes. Within a R&D project in France, the Centre National de la Recherche Scientifique (CNRS) developed one of the first high-temperature superconducting SMES with a capacity of 800 kJ and 400 kJ and Bi2212 material operating at 20 K\(^\text{33}\). At the Karlsruhe Institute of Technology (KIT) in Germany, a hybrid concept with a SMES, in combination with hydrogen, has been studied in detail\(^\text{34}\) and a first small MgB\(_2\) superconducting coil has been built and tested. This combines the fast SMES operation with bulk hydrogen storage and seems interesting for large capacities with liquid hydrogen storage. The Institut de Ciència de Materials de Barcelona (ICMAB) in Spain also developed SMES applications and built a demonstrator. Additionally, very recently, a new SMES project was launched in Italy with Columbus, ENEA, RES\(^\text{35}\), SPIN and the University Bologna to setup a 300 kJ, 100 kW SMES prototype system with MgB\(_2\) for a pioneering application in electricity systems. This last SMES application seems promising because studies have shown that a combination of SMES and battery systems could yield cost reductions and a significant increase in the lifetime of the battery system.

Mechanical Storage

Compressed Air

This energy storage system is differentiated between two technologies: Adiabatic Compressed Air Energy Storage (A–CAES) and Diabatic Compressed Air Energy Storage (D–CAES). Both systems are based on air compression and air storage in

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\(^{35}\) Reliable Environmental Solutions.
geological underground voids (mainly salt caverns). A–CAES systems are in the process of demonstration and are not yet commercially available. In recent years, several advanced projects, such as ADELE\textsuperscript{36} in Germany and AA–CAES\textsuperscript{37} in the UK, have been set up. In the future, A–CAES systems have the potential to provide a large part of the necessary European storage capacity, but this will depend on some geological characteristics in order to build underground storage capacity.

On the other hand, D–CAES systems are already deployed. There are two existing plants: one in Huntorf, Germany and one in McIntosh, Alabama, USA. The first R&D project started in Germany in 1978, after which the United States took the lead on D–CAES development. Currently, research is much more focused on upgrading D–CAES with a Thermal Energy Storage device, which can make deployment achievable within the coming years. This system is envisaged to increase variable renewable energy in the generation mix by 2030. Therefore, D–CAES is the only recognised and proven bulk storage technology other than PHS currently available on a commercial scale in Europe.

\textit{Flywheel}

Kinetic energy storage based on flywheels is characterised by a fast response, high power and energy density, as well as the possibility to decouple power and energy in the design stage. Flywheel is a mature technology completely introduced in the industrial market. More than 20 manufacturers have been identified and many research centres are focused on this technology as well. However, some technological aspects need to be improved. The industry for this sector is located mainly in the United States, as are the majority of R&D centres focused on flywheels.

In Europe, there flywheel projects are installed in in France, United Kingdom, Germany, Spain, the Portuguese islands, and, in particular, in Ireland where a hybrid flywheel plant was built in 2015\textsuperscript{38}. The Irish project (promoted by Schwungrad Energie\textsuperscript{39}) is attracting interest from national grids across Europe, which plan to

\begin{footnotesize}
\footnotesize

\textsuperscript{37} CORDIS: \textit{Advanced adiabatic compressed air energy storage (AA–CAES)} 2005. \url{http://cordis.europa.eu/project/rcn/67580_en.html}

\textsuperscript{38} The hybrid flywheel is a disruptive innovation with the potential to revolutionise the system services market, decoupling its provision from electricity generation by delivering energy–less system services

\textsuperscript{39} Company website: \url{http://schwungrad-energie.com/}
\end{footnotesize}
increase their renewable energy penetration in the years ahead\textsuperscript{40,41}. The flywheel project has received funding from both the European Commission and the Irish government.

\textit{Liquid Air}

Liquid Air Energy Storage (LAES), also referred to as cryogenic energy storage, uses liquid air as an energy vector. LAES technologies have been primarily developed by two British universities: the University of Newcastle upon Tyne and the University of Leeds. The former developed the LAES concept for peak shaving in 1977. The University of Leeds has carried out more research on LAES in collaboration with the British company Highview Power Storage and the Japanese company Mitsubishi Heavy Industries and Hitachi. Europe, and more particularly the UK, was thus at the forefront of the development of LAES technologies.

Today, the UK remains a world leader in LAES technologies. Highview Power Storage is building one of the first pre-commercial LAES technology demonstrators. Supported by UK government funding of more than £8 million, this 5 MW LAES technology system is expected to begin operations in 2017.\textsuperscript{42} Thus, the combined work of technology and innovation centres, growth-hungry companies with government support enabled the UK and thus Europe to become the world leader in term of LAES.

\textit{Pumped Hydro Storage (PHS)}

PHS is the largest storage technology in Europe (and indeed, worldwide). Currently, more than 50 GW net pumped hydro storage capacity\textsuperscript{43} (around 30% of global capacity) is in operation in the EU, representing 12% of total net electrical installed capacity in the EU\textsuperscript{44}. By 2020, installed PHS capacity in Europe is expected to reach 47.8 GW, a rise of almost 16% in 10 years\textsuperscript{45}, since PHS is the most mature and cost-effective large-scale storage solution available in Europe today.

\textsuperscript{40} Arthur Neslen: \textit{New energy storage plant could ‘revolutionise’ renewable sector}, The Guardian, 8 April 2015. \url{https://www.theguardian.com/environment/2015/apr/08/new-energy-storage-plant-could-revolutionise-renewable-sector}

\textsuperscript{41} Schwungrad: \textit{First Hybrid-Flywheel Energy Storage Plant in Europe announced in Ireland}, 2015. \url{http://schwungrad-energie.com/hybrid-flywheel-energy-storage-plant-europe-announced-ireland/}

\textsuperscript{42} Highview Power: \textit{Pre-Commercial LAES Technology Demonstrator}, 2017. \url{http://www.highview-power.com/pre-commercial-laes-technology-demonstrator/}


\textsuperscript{44} U.S. Energy Information Administration (EIA): \textit{Total Electricity Installed Capacity 2014}. \url{http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=7}

hydropower sector has a technology leadership role, as European equipment manufacturers account for two-thirds of the world market. In addition, three current global leaders accounting for more than 50% of the global hydropower equipment market are European companies\textsuperscript{46}.

Despite the large amount of capacity installed today, there is a huge potential for new expansion and development. The eStorage project estimates that 2291 GWh of development-ready sites with existing reservoirs for new pumped hydro energy storage plants exist in the EU–15, Norway, and Switzerland\textsuperscript{47}. Industry and R&D opportunities in PHS are focused on mountainous regions in Switzerland, Austria, Germany, Spain, and Portugal. Since conventional PHS plants can only regulate their power in generation mode, their operation in pumping mode is less flexible. Therefore, new technologies are being developed to enhance the operational flexibility of PHS plants\textsuperscript{48}.

**Thermal Storage**

**Sensible Heat**

The most common way of thermal energy storage (TES) is sensible heat. Underground TES are commonly used in Denmark, Sweden, the Netherlands, Norway and Germany for the sake of seasonal storage of heat in centralised and distributed energy systems\textsuperscript{49}. In these countries underground TES (UTES) is applied together with renewable solar or geothermal heat and electricity from photovoltaic, in combination with district heating, whereas in other European countries UTES systems are still on a demonstration and pilot level.

R&D is focused on the system and material level in order to achieve SET–Plan Targets on storage density (in general sensible heat storage requires large volumes because of its low energy density). Several developers in Germany, Slovenia, Japan, Russia, and the Netherlands are working on new materials and techniques for TES systems, including their integration into building walls and transportation of thermal energy


from one place to another. These new applications are now being commercialised, and their cost, performance, and reliability will be verified\(^{50}\).

**Latent Heat**

This type of TES could be a new useful device, suitable for grid applications. Its high heat capacity and the melting temperature of silicon made it ideal for storing a large amount of energy. Over the last four years, there has been a strong development in the sector and a year from now a prototype will start to operate. Australia has a burgeoning latent heat storage industry\(^ {51}\) supported by the Australian government\(^ {52}\). In Europe there are some ongoing research programs such as the one in Belgium, led by the EnergyVille research Centre of KU Leuven, which is trying to find better solutions for latent heat technology in terms of material improvements\(^ {53}\). Moreover, in Germany, Fraunhofer ISE has two research projects concentrated on Phase Change Materials\(^ {54}\).

**Thermochemical storage**

Thermochemical storage (TCS) is the third category of TES and is considered as the least investigated storage technology though it can potentially store more energy than sensible and latent heat\(^ {55}\). TCS is a very promising storage field because it could offer a higher energy density and even more important minor energy losses compared to the other TES\(^ {56}\).

Europe has been a pioneer in terms of thermochemical storage studies. The first TCS studies were published in the 1970s by Swedish and Swiss researchers\(^ {57}\) and a first practical TCS application – the ADAM–EVA project – was launched in Germany in the


\(^{51}\) 1414 Degrees website: http://www.latent-heat.com/


early 1980s\textsuperscript{58}. In 2016, thermochemical heat storages remain largely at an experimental stage. With respect to systems based on chemical reactions, 95\% of installed systems are in R&D. Sorption storage systems are slightly more developed with the exception of sorption heat pumps which have been fully commercialised. The EU-financed TCSPower project and the CWS project, both German, are two examples of recent TCS R&D projects.

6. Energy Storage Technologies

6.1 Chemical Energy Storage

Introduction
Chemical energy storage is based on the transformation of electrical energy into the energy of chemical bonds. It allows an exchange of energy between different vectors of the energy system, establishing cross-sectorial links of the power sector with the gas, fuel and chemical sectors. The heading Power-to-X (P2X) groups a range of generic technologies that convert renewable electricity into hydrogen, with the possibility to combine it with CO$_2$ to synthesise valuable gases (Power-to-Gas) and liquids (Power-to-Liquid) which can be used as fuels or chemicals.

a) Hydrogen

Electrolyser technology uses electricity to split water (H$_2$O) into hydrogen (H$_2$) and oxygen (O$_2$). Alkaline electrolyser technology is well known and has been utilised for about a century. Higher power density and efficiency is obtained with proton exchange membrane (PEM) cells. Recent developments include high temperature ceramic electrolyzers based on solid oxide technology, which can make use of CO$_2$ and produce syngas or synfuels and plasma-chemical conversion or plasmolysis to split CO$_2$ or water through vibrational excitation of the molecules in thermal non-equilibrium.

Hydrogen plays a central role in chemical energy storage. However, its low volumetric energy density requires compression of usually between 200 and 700 bar or liquefaction. Hydrogen has an extended versatility of use: it can be reconverted to electrical energy for stationary applications (power and heat generation) or mobile applications (transport) giving only water vapour as a reaction product, transmitted in dedicated pipelines to connect production sites with consumer sites, admixed into the existing natural gas grid to a certain limit, converted to others fuels (methane, methanol) or used in the chemical industry.

b) Other chemical energy carriers:

In order to increase volumetric energy density and make use of existing infrastructure, other energy carriers and chemicals using hydrogen, carbon dioxide or nitrogen can be used either as fuels or basis material for chemical

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59 Indeed, hydrogen is the only realistic chemical storage option (except perhaps ammonia) to avoid CO$_2$ emissions for all end users. Other chemical carriers should therefore be considered primarily for systems including CO$_2$ capture and storage.
industry. These are mainly methane (CH₄), methanol (CH₃OH), and ammonia (NH₃).

**Maturity of technology chain components**

Figure 4 shows the technical maturity of various parts of the chemical storage chain:

![Diagram showing technical maturity of chemical storage components]

**Applications**

Chemical energy storage has a wide variety of applications, including:

- CO₂ emissions reduction
- Energy security (indigenous RES conversion into methane, liquid hydrocarbon fuel)
- Energy resilience (coupling electricity, gas, fuel, and chemical sectors)
- Use of existing infrastructure for storage, transport, and use
- Reduction of RES curtailment
- Island and remote location energy sufficiency
- Grid services (voltage, frequency stability): very fast reacting devices balancing variable renewable energy sources
- Energy arbitrage
- Seasonal energy storage (GWh to TWh scale)
- Electrification in the chemical industry by providing hydrogen carriers (H₂, NH₃) or C₁ building blocks (methane, methanol)
- Indirect electrification of aviation, marine sector and transport by cars and trucks by synthetic fuels based on electricity

SET Plan targets⁶⁰ for electrolysis and hydrogen storage technologies towards 2030 and beyond

Table 1: SET Plan targets Alkaline Technology

<table>
<thead>
<tr>
<th>Property</th>
<th>State-of-the-art</th>
<th>Target 2020–2030</th>
<th>Ultimate goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating current density (A/cm²)</td>
<td>0.2–0.5</td>
<td>0.1–1</td>
<td>0–2</td>
</tr>
<tr>
<td>Operating temperature (°C)</td>
<td>ambient – 120</td>
<td>ambient – 150</td>
<td>ambient – &gt;150</td>
</tr>
<tr>
<td>Operating pressure (bars)</td>
<td>1–200</td>
<td>1–350</td>
<td>1–700</td>
</tr>
<tr>
<td>Durability (h)</td>
<td>10⁵</td>
<td>&gt; 10⁵</td>
<td>&gt; 10⁵</td>
</tr>
<tr>
<td>Cyclability</td>
<td>poor</td>
<td>improved</td>
<td>high</td>
</tr>
<tr>
<td>Production capacity of electrolysis units</td>
<td>1–100 kg/hour (≈ 10–1000 Nm³/hour)</td>
<td>&gt; 100 kg/hour (≈ 1000 Nm³/hour)</td>
<td>&gt; 1000 kg/hour (≈ 10 000 Nm³/hour)</td>
</tr>
<tr>
<td>Non–energy cost (€/kg H₂)</td>
<td>&lt;5</td>
<td>2</td>
<td>1</td>
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Table 2: SET Plan targets PEM Technology

<table>
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<tr>
<th>Property</th>
<th>State-of-the-art</th>
<th>Target 2020–2030</th>
<th>Ultimate goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating current density (A/cm²)</td>
<td>0 – 2</td>
<td>0 – 2</td>
<td>0 – 5</td>
</tr>
<tr>
<td>Operating temperature (°C)</td>
<td>50–80</td>
<td>80–120</td>
<td>100–150</td>
</tr>
<tr>
<td>Operating pressure (bar)</td>
<td>1–50</td>
<td>1–350</td>
<td>1–700</td>
</tr>
<tr>
<td>Durability (h)</td>
<td>10⁴</td>
<td>10⁴ – 5·10⁴</td>
<td>&gt; 10⁵</td>
</tr>
<tr>
<td>Production capacity of electrolysis units</td>
<td>1–30 kg/hour (≈ 10–300 Nm³/hour)</td>
<td>&gt; 30 kg/hour (≈ 300 Nm³/hour)</td>
<td>&gt; 100 kg/hour (≈ 1000 Nm³/hour)</td>
</tr>
<tr>
<td>Energy efficiency (kWh/kg H₂ at 80°C, 1 A.cm⁻²)</td>
<td>56</td>
<td>&lt; 50</td>
<td>48</td>
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<tr>
<td>Non–energy cost (€/kg H₂)</td>
<td>5</td>
<td>2</td>
<td>1</td>
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</table>

### Table 3: SET Plan targets Solid Oxide Technology

<table>
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<tr>
<th>Property</th>
<th>State-of-the-art</th>
<th>Target 2020–2030</th>
<th>Ultimate goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating temperature (°C)</td>
<td>800–950</td>
<td>700–800</td>
<td>600–700</td>
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<tr>
<td>Operating pressure (bars)</td>
<td>1–5</td>
<td>1–30</td>
<td>1–100</td>
</tr>
<tr>
<td>Operating current density (A/cm²)</td>
<td>0–0.5</td>
<td>0–1</td>
<td>0–2</td>
</tr>
<tr>
<td>Area Specific Resistance (Ω.cm²)</td>
<td>0.3–0.6</td>
<td>0.2–0.3</td>
<td></td>
</tr>
<tr>
<td>Enthalpic efficiency</td>
<td>100% at 0.5 A/cm²</td>
<td>100% at 1 A/cm²</td>
<td>100% at 2 A/cm²</td>
</tr>
<tr>
<td>Durability (h)</td>
<td>10³</td>
<td>10⁴</td>
<td>10⁵</td>
</tr>
<tr>
<td>Electrical modulation</td>
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<td>0–100</td>
<td>0–100</td>
</tr>
<tr>
<td>Load cycles</td>
<td>Unknown</td>
<td>10,000</td>
<td>&gt; 10,000</td>
</tr>
<tr>
<td>Start-up time (h)</td>
<td>12</td>
<td>1–6</td>
<td>&lt; 1–6</td>
</tr>
<tr>
<td>Production capacity of electrolysis units</td>
<td>&lt;1 kg/hour</td>
<td>10 kg/hour</td>
<td>100 kg/hour</td>
</tr>
<tr>
<td>Non-energy cost (€/kg H₂)</td>
<td>5</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 4: SET Plan targets Plasmology CO₂

<table>
<thead>
<tr>
<th>Property</th>
<th>State-of-the-art</th>
<th>Target 2020–2030</th>
<th>Ultimate goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power density (W/cm³)</td>
<td>10</td>
<td>100</td>
<td>1000</td>
</tr>
<tr>
<td>Enthalpic Efficiency (Enthalpy/power in)</td>
<td>50%</td>
<td>70%</td>
<td>80%</td>
</tr>
<tr>
<td>Operating temperature (°C)</td>
<td>ambient</td>
<td>ambient – 150</td>
<td>ambient – &gt;150</td>
</tr>
<tr>
<td>Operating pressure (bars)</td>
<td>0.2–0.5</td>
<td>0.5 – 1</td>
<td>1 – 1.2</td>
</tr>
<tr>
<td>Durability (h)</td>
<td>10⁵</td>
<td>&gt; 10⁵</td>
<td>&gt; 10⁵</td>
</tr>
<tr>
<td>Separation effluent gases in constituents</td>
<td>poor</td>
<td>improved</td>
<td>high</td>
</tr>
<tr>
<td>Use of scarce materials</td>
<td>None</td>
<td>None</td>
<td>None</td>
</tr>
<tr>
<td>Production capacity (kg/hr)</td>
<td>1</td>
<td>10</td>
<td>&gt; 100</td>
</tr>
<tr>
<td>Non-energy cost (€/kg CO)</td>
<td>&lt;1</td>
<td>0.1</td>
<td>0.05</td>
</tr>
</tbody>
</table>
Hydrogen Storage Technologies

Table 5: SET Plan targets Hydrogen Storage Technologies

<table>
<thead>
<tr>
<th>Storage Technology</th>
<th>Volumetric density (kg H₂/m³)</th>
<th>Gravimetric density (reversible) (wt %)</th>
<th>Operating pressure (bar)</th>
<th>Operating temperature (K)</th>
<th>Cost* ($ / kg H₂)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressed gas (H₂)</td>
<td>17 – 33</td>
<td>3 – 4.8 (system)</td>
<td>350 &amp; 700</td>
<td>ambient</td>
<td>400–700*</td>
</tr>
<tr>
<td>Cryogenic (H₂)</td>
<td>35 – 40</td>
<td>6.5 – 14 (system)</td>
<td>1</td>
<td>20</td>
<td>200–270*</td>
</tr>
<tr>
<td>Cryo–compressed (H₂)</td>
<td>30 – 42</td>
<td>4.7 – 5.5 (system)</td>
<td>350</td>
<td>20</td>
<td>400</td>
</tr>
<tr>
<td>High pressure – solid</td>
<td>40</td>
<td>2 (system)</td>
<td>350</td>
<td>243 – 298</td>
<td></td>
</tr>
<tr>
<td>Sorbents (H₂)</td>
<td>20 – 30</td>
<td>5 – 7 (material)</td>
<td>80</td>
<td>77</td>
<td></td>
</tr>
<tr>
<td>Metal hydrides (H₂)</td>
<td>&lt; 150</td>
<td>2 – 6.7 (material)</td>
<td>1 – 30</td>
<td>ambient – 553</td>
<td>&gt;500</td>
</tr>
<tr>
<td>Complex hydrides (H₂)</td>
<td>&lt; 120</td>
<td>4.5 – 6.7 (material)</td>
<td>1 – 50</td>
<td>423 – 573</td>
<td>300–450*</td>
</tr>
<tr>
<td>Chemical hydrides (H₂)</td>
<td>30</td>
<td>3 – 5 (system)</td>
<td>1</td>
<td>353 – 473</td>
<td>160–270**</td>
</tr>
</tbody>
</table>

* cost estimates based on 500,000 units production;  
** regeneration and processing costs not included

Gaps between targets and present performance

The major challenges for the chemical energy storage technology are related to costs, but many technical aspects need to be further developed to meet the SET plan targets. The investment costs (EUR/kW) need to be reduced to expand application areas for chemical energy storage, mainly with an up-scaling of the technology, more product standardisation, mass production and supply chain optimisation. On the technical side, higher efficiency, higher pressure, higher power density, and higher durability are the key challenges for all hydrogen technologies.

Research Priorities

Given the potential of chemical storage and P2X, an ambitious long term RD&D strategy is required at European level, following the example of the German Federal Ministry of Education and Research’s Kopernikus P2X programme, and the US Department of Energy’s Advanced Research Projects Agency – Energy (ARPA–E) REFUEL programme.

Research priorities include:

1. **Up-scaling of the technology** (multi–MW) via pilot and demonstration projects aiming at generating economies of scale, developing improved manufacturing methods (supply chain optimisation, standardisation and automation), and

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61 The establishment of demonstrators is hampered by the lack of incentives and insufficient regulatory situation.  
better integrating electrolyser technology with downstream processes with the overall objective of decreasing the total cost and improving efficiency.

2. Materials and electrochemical process research and development to **decrease the total cost** of the technology: use of low cost material, new designs and manufacturing methods, high current densities, large area cells, gas separation membranes, improved durability of the equipment, decreased use of noble metals, reduction of the service and maintenance needs, and increased energy density in hydrogen storage.

3. Materials and electrochemical process research and development to **improve the overall performance** of the technology: increase system efficiency, going to higher temperature, improve catalysts, high pressure electrolysis, improved interfacing between the various technologies and improved design of single equipment and the overall system.

4. **Research, demonstration and industrial optimisation of:**
   a. Catalytic formation processes for chemical fuels (gas or liquids) by conversion of hydrogen, nitrogen and CO₂ to: ammonia, methane, methanol, dimethyl ether (DME), oxy-methylene ether (OME), synthetic kerosene, formic acid, and other chemicals;
   b. The integration of these processes with upstream (renewables, electrolysers, CO₂ streams) and downstream processes (industrial processes, distribution networks);
   c. The applications using these chemical fuels: fuel cells, combustion engines, gas turbines.

5. Knowledge build up for health and safety, environmental compatibility (emissions, emission control), reduction of risk of pipeline leakage and corrosion due to hydrogen admixture, existing legal boundary conditions and their further development concerning: production of chemical energy carriers, storage, transport, handling and use, economy, sustainability of overall solutions.

**Recommendations for Research Funding, Infrastructure, and Incentives**

In the short term, R&D projects should continue to be supported via direct incentives to allow the up-scaling of technology, cost reductions, and a better integration of the various technologies. This requires general support for the entire chain including electrolysers, plasmolysers, compression and storage technologies, catalytic conversion technologies, and re-conversion technologies.

At EU level, we advise the creation of a 10-year R&D programme similar to the Kopernikus Power-to-X programme of the German Federal Ministry of Education and
Research (BMBF). As part of this programme, a national research platform is being established to focus on the development of key P2X technologies over the next ten years, with the support of a wide range of research institutions, industry players, and civil society organisations. The aim is to bring P2X solutions from the research or prototype stage to the deployment stage. One unique aspect of the programme is that it combines a long-term project structure with a flexible steering mechanism to adapt to the rapidly changing environment. The project is jointly funded by the BMBF and industry partners.

In the medium term (2020), direct incentives should be progressively replaced by market based incentives to recompense the renewable (or low-carbon) characteristics of the end product in the overall decarbonisation on the EU energy system comprising the power, gas, mobility and industrial sectors. Also on the regulatory side, a number of barriers preventing the competitiveness and deployment of chemical energy storage (e.g., high cost burdens from grid fees or other levies) must be removed.
6.2 Electrochemical Energy Storage

Batteries are electrochemical energy storage devices based on different specific chemical systems that are tailored to a variety of applications.

Until recently, the secondary (rechargeable) battery market could be divided into three segments:

1. Portable batteries (capacity < 6 Ah) used as a convenient power source for consumer devices (e.g., mobile phones or laptops): segment dominated mainly by the lithium–based batteries with the use of the nickel–based batteries in some specific niches.

2. Industrial batteries (capacity ≥ 6 Ah) used as a convenient power source for industrial devices either for stationary applications (e.g., UPS) or for mobile applications (e.g. forklifts): segment mainly dominated by the lead–based batteries with the use of nickel–based and sodium–based batteries in some specific niches.


In recent years, decarbonisation policies have led to the development of two new battery segments:

1. Mobility batteries used for “Clean Vehicles”:
   - Electric Vehicles (EV) and Plug–in Hybrid Vehicles (PHEV): dominated by lithium–based batteries
   - Hybrid Vehicles (HEV): lithium–based and Ni–MH batteries
   - Micro–Hybrid Vehicles: advanced lead–acid batteries with the use of lithium–based batteries for some niches

2. Storage batteries used to provide flexibility to the electrical grid: different battery technologies (lithium–based, sodium–based, lead–based, flow batteries, etc.) are used according to the battery location and the services provided. There is also a need for large–scale storage batteries to facilitate the integration of increasing shares of RES.

Batteries are based on single electrochemical cells, each having voltages ranging from below 1 V up to 4.1 – 4.2 V. The cells can be combined in series to yield very high voltages if required and the series cells are assembled in parallel to achieve the required power. Batteries hold highly attractive power densities and their round cycle efficiency (electrical energy out over electrical energy in) is generally high – in the range up to 70–95 %, depending on charge and discharge conditions. Because of the basic electrochemical cells of batteries, they are highly modular and can be manufactured for very high capacities and/or power requirements.

Electrochemical batteries consist of two or more electrochemical cells, which use chemical reactions to create a flow of electrons – electric current. Primary elements
of a cell include the container, two electrodes (anode and cathode), an electrolyte material (liquid or solid), and a separator membrane, which prevents a short contact of the electrodes. The electrolyte is in contact with the electrodes. Current is created by the oxidation–reduction process involving chemical reactions between the cell electrolyte and electrodes. When a battery discharges through a connected load, electrically charged ions in the electrolyte that are near one of the cell electrodes supply electrons (oxidation) while ions near the cell other electrode accept electrons (reduction), to complete the process. The process is reversed to charge the battery.

There are two categories of batteries:
- **Classical batteries** based on electrochemical charge/discharge reactions that occur between a positive electrode (cathode) and a negative electrode (anode) located in a cell. The electrodes are separated by a permeable membrane which allows for ionic flow between them and are immersed in an electrolyte.
- **Flow batteries** which use two liquid electrolytes – one in high oxidation state and one in low oxidation state – as energy carriers. They are separated using an ion–selective membrane, which under charging and discharging conditions allows selected ions to pass and complete chemical reactions at the cell level.

**Maturity of technology**

Of the current installed worldwide energy storage capacity, estimated at about 171,060 MW in 2016, electrochemical storage makes up approximately 1,639 MW\(^6^3\). This includes Li–ion (1,134 MW), sodium–based batteries (206 MW), flow batteries (74 MW), lead–based (110 MW), and nickel–based batteries (30 MW) according to the US Department of Energy. The battery storage market is currently small but will grow with the increase in grid flexibility needs if the battery performances reach the applications expectations. The maturity levels for various battery technologies are described in the table below.

**Table 6: Status of development of major electrochemical storage systems for grid applications**

<table>
<thead>
<tr>
<th>Status</th>
<th>Energy Storage technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mature</td>
<td>Lead–acid, Ni–Cd (nickel cadmium)</td>
</tr>
<tr>
<td>Commercial</td>
<td>Li–ion, Lead–acid, NaS (sodium–sulphur) and NaNi Cl2 (Zebra), supercapacitors</td>
</tr>
<tr>
<td>Demonstration</td>
<td>ZnBr (zinc bromine), advanced lead–acid, VR (vanadium redox), Li–ion, Zinc–air, Na–ion</td>
</tr>
</tbody>
</table>

The battery market is currently dominated by lead–based batteries but lithium–based batteries represent the highest growth rate, as shown in figure 5.

The global battery market was valued at $65 billion in 2015 (pack level) with a 5% average annual growth between 1990 and 2015\textsuperscript{64}.

\begin{figure}[h]
\centering
\includegraphics[width=\linewidth]{battery_market_growth.png}
\caption{Battery market growth (MWh) 1990–2015, Avicenne Energy, 2016}
\end{figure}

http://www.avicenne.com/reports_energy.php
Energy storage represents a different market for batteries with a specific value chain, as seen in the below figure:

*Figure 6: compilation by EMIRI, EUROBAT, EASE, and Technofi, 2016*

This complex value chain requires collaboration between five categories of suppliers at global level:

- Raw materials suppliers (metals, additives and solvents), which can be located in large chemical companies
- Advanced materials and component suppliers (anode material, cathode material, electrolyte, separators, binders, additives, cell housing) which can be located in large chemical companies or divisions of manufacturing companies
- Cell manufacturers
- Battery pack suppliers
- Storage integrators which, when considering grid applications, are located in each of major power system integrators

R&D efforts are important at all of these stages, not only at the electrochemical stage. In particular, R&D efforts supporting developments in the system integration of battery storage are particularly valuable for the European battery industry.

Batteries will require strong R&D efforts in order for them to be able to compete against other flexibility solutions such as flexible generation, grid upgrade, interconnections or demand response. Although some lithium-based solutions are already available and are already marketed for some grid storage applications, a significant decrease in the Levelised Cost of Stored Energy (LCOSE) is needed for the battery storage market to continue its rapid growth.
Some battery technologies, such as Li–ion, are expected to benefit from the R&D and industrial investments made for the automotive sector. The rapidly decreasing costs for EV battery packs (as seen in figure 7) are expected to have an impact on the energy storage batteries sector as a whole.

Figure 7: Cost estimates and future projections for electric vehicle battery packs, measured in US $ per kilowatt hour of capacity. Each mark on the chart represents a documented estimate reviewed by the study. Source: Nykvist et al. (2015)

Applications
Electrochemical storage systems are considered one of the key energy storage technologies enabling the transition from the current mostly centralised electricity generation networks to distributed ones with increasing penetration of variable and non–programmable renewable energy sources (e.g., wind and photovoltaic) and more “intelligent” management of the energy flows (with smart grids and “prosumers”, i.e. end–users with a more active role in the electricity market).

The different energy storage applications can be segmented according to the discharge time, as shown in figure 8.

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A schematic comparison, as presented in table 7, of the key applications with the various electrochemical storage technologies shows the extreme variability of possibilities and the effective suitability of each technology. 

Table 7: Comparison among different electrochemical storage systems for the different discharge times corresponding to the different energy storage applications

<table>
<thead>
<tr>
<th>Storage Segment</th>
<th>Storage Type</th>
<th>Storage Duration</th>
<th>Lead-acid</th>
<th>Ni-Cd</th>
<th>Li-Ion</th>
<th>NaS</th>
<th>NaNiCl2</th>
<th>Flow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Acting Storage</td>
<td>Power Quality</td>
<td>&lt; 1'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Power System Stability</td>
<td>1' → 15'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Storage</td>
<td></td>
<td>15' → 60'</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Storage</td>
<td>Daily</td>
<td>usually 6 h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Weekly</td>
<td>usually 30 → 40h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Monthly</td>
<td>168h → 720h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Seasonal</td>
<td>≥ 720h</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The most imminent business cases for grid application of batteries are expected to arise from demand for grid services as a result of increased penetration of variable RES in Europe and the parallel phasing out of fossil fuel plants, which have until now taken care of the services.

In addition, decentralised application of batteries in the low voltage end of the distribution grid is expected to become a business case from 2017–2018. Local solar power feed-in may lead to constraints in the low-voltage grid, which can be prevented by local storage capacity (e.g., a battery system). Storage can allow DSOs to defer reinforcement of the local grid (referred to as investment deferral), which is often an expensive path. Following the dramatic increase in solar power installations seen all over Europe and the ongoing drop of battery cost at a rate of 14% per year.
over the past 10 years, a €1 billion market for decentralised battery storage is expected to develop in the coming decades\(^68\). EV/PHEV batteries are expected to be involved in the grid flexibility with the V2G application on one hand and with the use of second-hand EV/PHEV batteries for grid storage on the other hand.

**SET Plan targets\(^69\) for batteries towards 2030 and beyond**

The main battery target is to get a Levelised Cost of Stored Energy (LCOSE) lower than the Levelised Cost of Energy (LCOE) of other flexibility alternatives such as flexible generators or grid upgrades.

With these priorities in mind, the SET Plan defined some targets for the stationary battery systems in 2030:

- System efficiency > 90%\(^70\)
- System cost < €150/kWh (for a 100kW system)
- Lifetime of thousands of cycles

Further targets for the main battery technologies are indicated in the below tables. These figures are based on the targets identified by the European Commission in 2011, but have been slightly updated to reflect recent developments in battery technologies.

**Table 8: SET Plan targets for electrochemical storage**

<table>
<thead>
<tr>
<th>Technologies</th>
<th>Now</th>
<th>2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lead–acid</td>
<td>Energy cost &lt; 150–100 €/kWh or &lt;&lt; 0.08–0.04 €/kWh/cycle</td>
<td>Energy cost &lt; 150–100 €/kWh or &lt;&lt; 0.08–0.04 €/kWh/cycle</td>
</tr>
<tr>
<td></td>
<td>Temperature operating range for stationary applications: −30 to +50°C</td>
<td>Temperature operating range for stationary applications: −30 to +50°C</td>
</tr>
<tr>
<td></td>
<td>Specific performances: 40–60Wh/kg and 140–250 Wh/L</td>
<td>Specific performances: 40–60Wh/kg and 140–250 Wh/L</td>
</tr>
<tr>
<td></td>
<td>Cycle life: &gt; 3,000 (80% DoD) −10,000 cycles (60% or 80% DoD)</td>
<td>Cycle life: &gt; 3,000 (80% DoD) −10,000 cycles (60% or 80% DoD)</td>
</tr>
</tbody>
</table>


\(^70\) This target is only achievable with Li–ion or Na–ion. Energy efficiency is by nature lower in aqueous systems (i.e. Ni–Cd, Zn–air or lead–acid) and in high temperature batteries; none of them will enable such high system efficiencies.
<table>
<thead>
<tr>
<th>Technology</th>
<th>Specific Energy</th>
<th>Energy Density</th>
<th>Cost</th>
<th>Power</th>
<th>Life Time</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Li-ion (cell level)</strong></td>
<td>274 Wh/kg (^{71})</td>
<td>700 Wh/l</td>
<td>250 €/KWh</td>
<td>3 000 W/kg</td>
<td>5000 cycles (C anode)</td>
<td>High stability</td>
</tr>
<tr>
<td></td>
<td>320 Wh/kg</td>
<td>800 Wh/l</td>
<td>150 €/KWh</td>
<td>10 000 W/kg</td>
<td>10 000 cycles (C anode), 60,000 cycles (Li-ion titanate)</td>
<td>No Hazard</td>
</tr>
<tr>
<td><strong>Flow Batteries</strong></td>
<td></td>
<td></td>
<td>250 €/kWh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>High temperature:</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(Sodium-based)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Cost</td>
<td>X/kWh</td>
<td>3 000 €/kW</td>
<td>Y/kWh</td>
<td>1 500 €/kW</td>
<td>$0.04--$0.75/kWh/cycle</td>
<td>$0.01--$0.08/kWh/cycle</td>
</tr>
<tr>
<td>Cycle life cost</td>
<td>$0.04--$0.75/kWh/cycle</td>
<td>1 500 €/kW</td>
<td>$0.01--$0.08/kWh/cycle</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Na-Ion</strong></td>
<td>90 Wh/kg (Aquion)</td>
<td>110 Wh/kg</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Energy</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Metal-air Systems</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Zn-Air</td>
<td>$ 160/200/KWh for a 1MW/4MWH system (EOS)</td>
<td>700 Wh/kg (Li air Polyplus)</td>
<td>150 cycles(^{72})</td>
<td>&gt;500 Wh/kg, 300--500 €/kWh</td>
<td>3000 cycles</td>
<td></td>
</tr>
<tr>
<td>Li-air</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Specific Energy</td>
<td>120 Wh/kg, 1 400 cycles at system level (48V/3 kWh: Oxis) or 350 Wh/Kg, 100 cycles at cell level (Oxis)</td>
<td>400 Wh/kg, 3000 cycles at cell level</td>
<td>150 €/kWh</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

\(^{71}\) Achieved for consumer cells (18650) with limited cycle life time. Industrial cells achieve about 170 Wh/kg today.

When looking at the above targets, one should keep in mind that it can be difficult or impossible to achieve all performance criteria for a given technology concurrently (e.g. life time versus energy density). Furthermore, some performance parameters strongly depend on use conditions (e.g. cycle life depending on frequency of fast charge).

**Gaps between targets and present performance**

- **Lead–acid technology**: there is a need to improve its cycle life time and operation at partial state of charge without increasing investment costs (€/kWh).

- **High temperature battery technology** (sodium based): it must simultaneously improve its life time (cycle life time and calendar life time) and decrease its investment costs (€/kW).

- **Li–ion technology**: although Li–ion batteries are commercially available in large systems and offer considerable advantages already today, there are still significant potential for improvements both in performance and in cost. A further reduction of LCOSE will broaden the spectrum of grid applications that are becoming economically viable with storage. The decrease in LCOSE is expected to be reached by improvements in production technology, value chain restructuring, the use of low cost materials, the increase of the specific energy, and the increase in life duration (cycle life and calendar life). Another possibility will be the use of second hand batteries provided by the transport sector. A clearer standardisation into three segments (power/hybridisation battery, lowest cost option, range option) can be expected. Appreciable gains in terms of performance are expected from all–solid–state batteries, including those still in early development stage.

- **Li–S technology**: it must improve both its cycle and calendar life time, increase its energy density using less electrolytes, and reduce its high level of self–discharge. The use of metallic lithium as anode can lead to improvements in safety.

- **M–air technology**: only Zn–air batteries are currently available for demonstration purposes. This technology must improve its round–trip efficiency and its power–to–energy ratio. Li–air are at prototype level and must improve their cycle life and energy density (tested in air and not only in pure oxygen).

- **Na–ion technology**: only Na–ion batteries based on a neutral pH aqueous based electrolyte are available for demonstration purposes. No suitable cathode materials exist today at industrial scale. This technology must improve its specific energy, energy density, and power capability. Similarly to Li–ion batteries, solid–state concepts should increase these values. Na–ion technology will also require sufficient cost reductions in order to displace Li–ion.

- **Flow battery technology**: the two key strengths of flow batteries for grid scale storage are related to long lifetimes with a proven capability to operate over more
than ten thousand charges and the ability to decouple power and energy. This offers flexibility for a wide range of applications requiring either high power or high energy. However, key challenges in two main R&D areas should be addressed: substantial cost reduction of the flow battery systems (membrane and materials), better life time of the membrane, and possibly improvements in power and energy density.

**Research Priorities**

The main priority for R&D efforts is to decrease the LCOSE of the batteries for each relevant energy storage application or aggregate of relevant energy storage applications. The following focus areas are proposed for research in electrochemical energy storage:

1. Immediate priorities are improvements to the cycle life and overall calendar life as well as the safety and the fast charging ability of all battery technologies addressing the relevant degradation mechanisms.

2. Intensive research focused on materials and their processing (e.g. local tailoring of materials properties or electrode architectures with thin film, plasma or laser technology) for the most attractive battery technologies will be required for substantial breakthroughs and increased applicability for batteries to grid applications. Each technology has the potential for significant further technical improvement, and all can provide distinctive and important functions to grid operators. However, Li–ion technologies are particularly promising, and research on Si–based and LTO–based anodes for their respective niches, as well as high voltage cathodes, would be valuable areas of research.

3. It is essential to develop mechanical system designs with light structural materials, as well as efficient and low cost thermal management systems. Battery operating system weight and thermal management are important areas for system improvements sometimes easier to achieve than electrochemical improvements.

4. Research should be directed both at improving performances at the battery cell level, and battery system design level (connectors, battery management system, interaction with the grid, etc.). Research on the chemistry itself has also high potential as it has not been carried out sufficiently for these new functionalities. Research should also focus on intelligent battery management, including the electronics and systems for quality control and battery “smartness”.

5. Exploratory research, using for instance combinatorial materials approaches, is strongly recommended on novel materials for completely new electrochemical systems (e.g., metal–air, liquid batteries, all–solid–state batteries, Mg–based batteries, organic batteries, fluoride–ion, chloride–ion, other conversion–based systems, battery cells up to 5V) with the additional targets for the 2020–2030
period to further reduce the battery cost by more than 40%. Particular attention should be paid to utilising raw materials which will not be foreseen as scarce or environmentally problematic. In general, the targeted technical and economical performances of the emerging electrochemical technologies may be estimated to be in the Horizon 2020–2030: more than 500 Wh/kg, more than 3000 complete charge/discharge cycles and a cell cost below 350 €/kWh.

6. Intensive research efforts should be carried out at the grid integration level in order to decrease storage system costs and to facilitate the aggregation of different applications.

7. There is also a need for intensive research on synthesis and new manufacturing processes in order to decrease the battery cost at both the cell and system level.

8. Research and demonstration on the use of second hand batteries (mainly Li–ion batteries) provided by the transport sector for stationary storage could yield valuable insights into ageing processes and their correlation safety. Also, research and demonstration is needed for the V2G concept, particularly with regards to the impact of dual applications on battery life.

**Recommendations for Research Funding, Infrastructure, and Incentives**

A predominantly research–directed effort on improved or brand–new electrochemical storage systems is required. Funding of at least 50–70 M€ per year would be necessary to reach significant electrochemical improvements. The most effective approach will be to focus on research yielding continuous improvements and cost reductions. It will also be important to support research laboratories focused on basic and applied materials research and electrochemical development, with advanced research infrastructure and modelling tools, complete investigation of safety and degradation mechanisms, up to complete engineering and full–scale demonstration. Moreover a well–coordinated European network of joint research between industry, academia, and large research centres on electrochemical energy storage should be established, as it is urgently needed to reach a low–carbon future, cement European leadership, and support the creation of new jobs.
6.3 Electrical Energy Storage

Supercapacitors

Introduction
Electrochemical capacitors (ECs), also referred to as “supercapacitors” or “ultracapacitors,” store electrical charge in an electric double layer at the interface between a high-surface-area carbon electrode and a liquid electrolyte. Consequently, they are also referred to as electric double layer capacitors (EDLC). Since this mechanism is highly reversible, ECs, exactly like conventional capacitors, can be charged and discharged at high power rates thousands of times with low capacitance fade. The electrode surface area in capacitors determines the capacitance and thus, the energy storage capability of the device. The amount of energy stored by ECs is very large compared to conventional capacitors because of the use of a porous carbon–based electrode material of high surface area.

While supercapacitors have very high specific power (10–20kW/kg) relative to batteries, they have a low specific and volumetric energy density (<8Wh/kg). One related chemistry that seeks to improve the energy density of supercapacitors while maintaining high power capability, cyclability, and lifetime is the lithium–ion capacitor (LCAP). The LCAP features a positive electrode similar to a supercapacitor electrode, while the negative electrode contains partially intercalated lithium. State–of–the–art technology indicates a two– to three–fold increase in energy density relative to a supercapacitor, with a similar discharge profile and cycling capability.

Maturity of technology
Supercapacitors have a short history dating back to their first discovery in 1957. Niche uses have been seen since the early 1980s and a broader use of ECs has accelerated over the last 15 years in particular. Supercapacitors are now widely commercialised in hybrid bus, rail, and automotive applications, as well as back–up power applications such as wind pitch control systems and uninterrupted power supplies. They are in the demonstration/piloting phase for grid energy storage systems as a stand–alone technology or hybridised with a second, low–cost high energy density technology, such as flow batteries and high energy Li–ion batteries.

LCAP technology has been in development for nearly a decade and piloting is anticipated over the next several years in both transportation and grid energy storage applications.
Applications
ECs are very suitable for high-power applications and are therefore witnessing growing interest from electric utilities, which are looking to these devices for performance improvement and reliability in a variety of areas, with much higher power levels and with transmission voltages up to 12kV and distribution voltages up to 1500V. The key features of ECs are extremely appealing for a variety of applications in electricity grids: fast response time in milliseconds, high energy efficiency (more than 95%), high power density, and long calendar and cycle life. A number of valuable functions can be performed by EC devices in electric grids, such as:

1. *Transmission line stability*: the stability of a transmission system can be improved by adding energy storage. This serves to dampen oscillation through the successive generation and absorption of real (as opposed to reactive) power. There is also transient stability – the stability required after a utility event (loss of substation or major line). During a transient event, achieving stability requires a substantial capability to absorb energy quickly. This is somewhat analogous to “dynamic braking” because generator turbines must be slowed. A typical specification is 100 MW with 500 MJ (< 5 s).

2. *Spinning reserve*: this is the generation capacity that a utility holds in reserve to prevent service interruptions if a generator fails. An ultracapacitor system can be built to supply power during the interruption, until quick-start diesels begin to supply power. A typical specification is 20MW to 100MW and 300 MJ to 1500 MJ.

3. *Area and frequency control*: the mismatch between electrical energy production and energy consumption (including losses) appears as a frequency variation. EC systems, thanks to their fast response time, would be considerably more effective than a generating plant in supplying frequency regulation. A system based on EC can absorb or supply energy as required, freeing other generation sources from frequency regulation or tie-line control duties. A typical specification is 100 MW to 1000 MW and 0.1 MWh to 10 MWh.

4. *Renewables intermittency smoothing*: power output from a renewable source such as solar can fluctuate by over 50% on a second–by–second basis. Ultracapacitors can rapidly inject power into a grid or microgrid to stabilise power output. A typical specification is 1– 500 MW and 0.1 to 5 MWh.
## SET–Plan Targets

### Table 9: SET Plan targets for supercapacitor* technologies towards 2030 and beyond

<table>
<thead>
<tr>
<th>Current performance</th>
<th>Target 2020–2025</th>
<th>Target 2030</th>
<th>Target 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>≈ 4–8 Wh/kg EDLCs</td>
<td>&gt;20–30Wh/kg</td>
<td>≈50Wh/kg</td>
<td>Electrolyte stability ca. 4.5–5V</td>
</tr>
<tr>
<td>≈ 10–15 Wh/kg</td>
<td>Voltage stability ca. 3.5–4V</td>
<td>Voltage stability ca. &gt; 4V</td>
<td>ca. 3000 m2g active area</td>
</tr>
<tr>
<td>Li-ion capacitors</td>
<td>ca. 0.1–0.5 c€/F</td>
<td>ca. 0.1 c€/F</td>
<td>ca. 600 F/g</td>
</tr>
<tr>
<td>≈10–20kW/kg (1–5s)</td>
<td>Low T °C (-40°C)</td>
<td>Low T °C (-40°C)</td>
<td>Energy close to power</td>
</tr>
<tr>
<td>(500 k – 1M cycles</td>
<td>High T (&gt; 85°C)</td>
<td>High T (&gt; 85°C)</td>
<td>batteries (50Wh/kg)</td>
</tr>
<tr>
<td>depending on systems)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low T °C (-20°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High T (&gt; 65°C)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*Supercapacitors (EDLC, Li–ion capacitors, Pseudo capacitors, hybrid, symmetric and asymmetric systems)

### Table 10: Economic SET Plan targets for supercapacitor technology towards 2030

<table>
<thead>
<tr>
<th>Current performance</th>
<th>Target 2020–2030</th>
<th>Target 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>• &gt;7Wh/kg</td>
<td>10–30 Wh/kg</td>
<td>Electrolyte stability ca. 4.5–5V</td>
</tr>
<tr>
<td>• 10–20kW/kg (1–5s)</td>
<td>15–25kW/kg (1–5s)</td>
<td>ca. 3000 m2g active area</td>
</tr>
<tr>
<td>• ca. 1500–2000 m²/g</td>
<td>500,000 – 1,000,000 cycles (depending on application)</td>
<td>ca. 600 F/g</td>
</tr>
<tr>
<td>• &gt;1,000,000 500,000 – 1,000,000 cycles (depending on application)</td>
<td>Low °C (~40°C)</td>
<td>Energy close to power</td>
</tr>
<tr>
<td>• Low °C (~40°C)</td>
<td>High T (~ 85°C)</td>
<td>batteries (50Wh/kg)</td>
</tr>
<tr>
<td>• High T (~ 85°C)</td>
<td>€0,3/W (cell basis)</td>
<td>€0,05/W (cell basis)</td>
</tr>
</tbody>
</table>

## Gaps between targets and present performance

ECs are interesting for their capacity to store very high power in a small volume and weight with high stability over a long period time. The storage system round–trip efficiency is extremely high, at around 95%.

Driven by economies of scale and advancements in manufacturing, the cost of supercapacitors has decreased dramatically for their deployment in grid energy storage systems. At present, fully installed costs are estimated to be $1000/kW and are expected to decrease to $517/kW by 2021. Given this customer value improvement and the ability to pair with batteries to “stack” grid services and improve battery lifetime, supercapacitors are now being piloted in systems across the globe.

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74 Navigant Research, May 2016
Research Priorities
The following topics are key research priorities for ECs over the next decades:

1. Finding electrolytes capable of voltages beyond 3.0 V, preferably with less toxicity. One route to achieve this will be the development of ionic liquids and new conducting salts for higher voltage ranges with wide operational temperature ranges and high conductivity. Ionic liquids–solvent mixtures with high voltage solvents as developed in Li ion batteries (additives/new solvents).

2. Proof of concept of asymmetric LCAP systems: improve life cycle and improve symmetry of charge–discharge rates to achieve 20–30 Wh/kg in synergy with high power Li–ion batteries; proof of concept of ceramic EC with dielectric or insulator with very high permittivity.

3. Basic and applied research on aqueous hybrid systems for very low cost and low environmental impact using activated carbons.

4. There are extraordinary opportunities that may come from the use of pseudo capacitive charge storage materials, which can lead to much higher levels of charge storage than ECs because of redox reactions. Improved understanding of charge transfer processes in pseudo capacitance is a critical step that will lead to the design of new materials and multifunctional architectures offering substantially higher energy density and at high discharge/charge rates. Novel transition metal oxides of lower cost, eco–friendly (e.g. MnO$_2$) and better performances need to be explored for EC applications because of their layered structure and ability to adopt a wide variety of oxidation states.

Further interesting research issues are to reduce component and finished electrode material manufacturing costs and to increase the capacitance of electrodes by enlarging the surface area and tailoring the pore size and shape. Figure 99 summarises the roadmap of ECs with projections towards 2030, in which are evidenced the future visions on development of new high performance materials for electrodes and electrolytes.
Figure 9: Tentative Roadmap for supercapacitors with vision to 2030 (prepared by CNR–ITAE from75).

Recommendations for Research Funding, Infrastructure, and Incentives

A predominantly research–directed effort on new supercapacitive systems is required. Funding in the range of at least €10–15 million per year would be necessary to reach significant EC improvements. As indicated, this effort is anticipated in research laboratories, while European industry is expected to contribute with only a minor part. In particular, research should focus on (large–scale) demonstration projects because for grid applications the most common use of supercapacitors in Uninterruptible Power Systems (UPS) has been complemented by few demonstration projects.

Research infrastructure should enable clustering of research groups in Europe as well as organisation and effective distribution of efforts between electrochemical research centres in Europe. The full benefit of European electrochemical storage potential can only be reached by integrating and complementing current national and European research programs and projects for optimal utilisation of resources and efforts, as is underway in EERA collaborations. A stronger and more intelligent coordination of resources (both central EU resources and national resources in member states) will improve the overall outcome to the benefit of the European population.

Superconducting Magnetic Energy Storage (SMES)

Introduction
SMES has been of scientific interest for years\textsuperscript{76,77,78,79,80} and still requires a considerable development effort to demonstrate its economic potential. Long–term rather basic R&D efforts are required, but these will likely pay off since the technology may hold considerable potential.

In SMES systems, the energy is stored in the magnetic field of superconducting coils, thereby exploiting the ultra–low losses of superconductors which allows a very fast delivery of high power (ms) at high cycle efficiency (>95 %), even if the cooling is accounted for. Other key issues are a high robustness, full charging and discharging, and a long lifetime with a virtually unlimited number of cycles.

To date, the cost for the cryogenic infrastructure has prevented a broader utilisation of SMES, but the new superconductors which can be operated at higher temperatures, the so called High–Temperature Superconductors (HTS), now provide a concrete perspective for new engineering designs. In addition, a combination of SMES with large–scale storage systems (such as electrochemical storage systems, Compressed Air Energy Storage (CAES) or cryogenic storage), can provide the robustness, high–speed, high peak power, high efficiency, and long life characteristics for achieving a complete storage system capable of complementing the lower speed response and protecting against sudden power demands. The high flexibility of such a robust, powerful, fast, and efficient buffer allows a better dimensioning of the long–term energy storage systems. Typical applications could be found at the customer level

\textsuperscript{78} A. Bautista ; P. Esteban ; L. Garcia–Tabares ; C. Peon ; E. Martinez ; J. Sese ; A. Camon ; C. Rillo ; R. Iturbe, \textit{Design, manufacturing and cold test of a superconducting coil and its cryostat for SMES applications}, IEEE Transactions on Applied Superconductivity Volume: 7, Issue: 2, June 1997, DOI: 10.1109/77.614637.
\textsuperscript{79} H. Salbert ; D. Krischel ; A. Hobl ; M. Schillo ; N. Blacha ; A. Tromm ; W. Roesgen, \textit{2 MJ SMES for an uninterruptible power supply}, IEEE Transactions on Applied Superconductivity, Volume: 10, Issue: 1, March 2000 , DOI: 10.1109/77.828346
\textsuperscript{80} T. Katagiri ; H. Nakabayashi ; Y. Nijo ; T. Tamada ; T. Noda ; N. Hirano ; T. Nagata ; S. Nagaya ; M. Yamane ; Y. Ishii ; T. Nitta, \textit{Field Test Result of 10MVA/20MJ SMES for Load Fluctuation Compensation}, IEEE Transactions on Applied Superconductivity, Volume: 19, Issue: 3, June 2009, DOI: 10.1109/TASC.2009.2018479.
(e.g. industrial parks, petrochemical centres) or at the generation level (e.g. wind farms) where energy quality and levelling are of high relevance.

Among the long term–short term hybrid storage systems in development, including the symbiotically linked cryogenic energy storage, a new multi–functionality hybrid energy storage system, LIQHYSMES, (see Figure below) has been proposed which combines the use of LIQUid HYdrogen (LH₂) with SMES. The LIQHYSMES Storage Unit (LSU) as the core element integrates the H₂ liquefaction part, the LH₂ storage tank and the SMES cooled by the LH₂ bath. This allows jointly utilising the cryogenic infrastructure and drastically reducing the otherwise significant H₂ liquefaction losses and the cost.

![Figure 10 – SMES buffering of mechanical, chemical, electrochemical or cryogenic Energy Storage Systems](image)

The LIQHYSMES approach offers substantial gains with up-scaling both in terms of efficiency and cost reduction, and thus addresses especially the range of tens to hundreds of MW and GWh.

![Figure 11 – LIQHYSMES Storage Unit based on hydrogen for long term energy storage and SMES for short term storage](image)

Maturity of technology

SMES based on Low Temperature Superconductors (LTS) have been built up to a power of 10 MW and a capacity of 20 MWs\(^2\). Qualified LTS SMES systems have proven in several long-term field tests that they can fulfil all technical requirements. Several companies have started to offer LTS SMES commercially. Since 2011, three LTS SMES units with deliverable power of 10 MW have been in operation in Japan for bridging instantaneous voltage dips of critical industrial customers.\(^3\) Due to the relatively high system cost, however, LTS SMES has not been able to find a wider market up to now. The maturity of LTS SMES has reached Technology Readiness Level (TRL) 8, meaning that several systems were completed and qualified through testing and demonstration.

The discovery of high-temperature superconducting (HTS) materials and the ongoing development of the 2G superconducting wires, known as coated conductors, open a window for a new class of HTS SMES to work at higher temperatures (up to 50 K), higher magnetic flux densities (up to 20 T), and even higher efficiencies. The success in the production of HTS wires and tapes with an increasing number of producers and a decreasing cost performance ratio envisages that a modular MW class HTS SMES could be an attractive device. To date, 2.5 MW HTS SMES have been designed\(^4\) which means that a TRL of 5 to 6 has been reached. Further improvements towards larger magnetic flux density systems, coil manufacturing, HTS winding cable, and cooling simplification are ongoing.

A hybrid energy storage based on a SMES in combination with other storage technologies has been studied\(^5\),\(^6\) for different combinations but not more than a proof of concept and small laboratory experiments on a TRL of 3 have been

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\(^4\) Lee, S; Yi, KP; Park, SH; Lee, JK; Kim, WS; Park, C; Bae, JH; Seong, KC; Park, I; Choi, et al, Design of HTS Toroidal Magnets for a 5 MJ SMES, IEEE Transactions on Applied Superconductivity, Volume: 22, Issue 3, DOI: 10.1109/TASC.2011.2175871

\(^5\) Li, J., Zhang, M., Yang, Q., Zhang, Z. and Yuan, W., 2016. SMES/battery hybrid energy storage system for electric buses. IEEE Transactions on Applied Superconductivity, 26 (4), 7403905, DOI: 10.1109/TASC.2016.2527730

\(^6\) Jianwei Li, Anthony M. Gee, Min Zhang, Weijia Yuan, Analysis of battery lifetime extension in a SMES-battery hybrid energy storage system using a novel battery lifetime model, Energy 86 (2015) 175–185, DOI: 10.1016/j.energy.2015.03.132.
performed. Nevertheless, this seems attractive because it combines the benefits of SMES with a large storage capacity.

**Applications**

Since SMES provide high power in a short time and are rather limited in their energy storage capacity, they are suitable to enable pulsed power supply (e.g. accelerators), to improve power quality at the customer or generator side, to contribute to voltage control and reactive power compensation, to improve transient stability, and to provide Uninterruptable Power Supply (UPS). Given its ability to withstand a practically unlimited number of cycles, SMES is also suitable where fast and continuous charge/discharge operation is required.

SMES plants do not depend on specific geological formations, they can be positioned everywhere, and consequently markets should be addressable everywhere in the world where these applications are needed.

Highly industrialised regions characterised by a high level of digitisation and particular needs for high quality supply would then particularly benefit from the ancillary services of the SMES. Potentially attractive locations in the electricity network might be those where the SMES plants can be combined with other existing or foreseen grid components, e.g. with reactive power control, AC–DC / DC–AC conversion, transformers or circuit breakers.

Hybrid energy storage systems, consisting of SMES in combination with electrochemical energy storage, can be attractive for providing both high power and high energy capacity with extended lifetime and reduced overall costs. Potentially attractive locations for a LIQHYSMES in a future H₂ supply network might be those where the LIQHYSMES plant can be combined with the production, storage, and distribution of H₂.

**SET–Plan Targets**

The SET Plan targets taken for the material development roadmap are given in table 11. Due to the rapid development of 2G HTS wires and tapes, these targets seem outdated. Therefore, new targets for SMES materials, SMES technology, and SMES systems are proposed in table 12.

<table>
<thead>
<tr>
<th>Current performance</th>
<th>Target 2020–2030</th>
<th>Target 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Highly efficient &gt;95 %</td>
<td>Increasing critical T° of the superconductors</td>
<td>Cost reduction &gt;5–10%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ca. 100 €/kW (200€/kWh)</td>
</tr>
</tbody>
</table>

59

EASE/EERA European Energy Storage Technology Development Roadmap

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For short duration storage (electricity stored in magnetic field)  
Superconducting coil cooled below its critical $T^\ast$

| 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 |

Table 12: Targets for SMES materials, technology and systems towards 2030 and beyond

<table>
<thead>
<tr>
<th>Current performance</th>
<th>Target 2020–2030</th>
<th>Target 2050</th>
</tr>
</thead>
</table>
| Highly efficient >95 %  
For short duration storage (electricity stored in magnetic field)  
Superconducting coil cooled below its critical $T^\ast$ | 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 |

Gaps between targets and present performance

Challenges exist both in the field of new superconducting materials and adapted novel designs and systems essentially based on modularity. The main gap is between the present and envisaged cost/performance ratio of the superconductors and the economy and maintenance of the cooling systems. The gap in the cost/performance ratio of the superconductor can be closed by further R&D resulting in increased wire performance and by introducing industrial production methods to further reduce the wire cost. A further gap is that HTS SMES have not proven operation in long–term field tests where it can be demonstrated that all user requirements can be fulfilled.

Hybridisation with external cryogen sources should be complemented with cooling machines able to work between the intermediate temperature of industrial liquid cryogenic gases as LN$_2$ or LCH$_4$ and the superconducting requirements. Enhancing the power of the existing low temperature rejection cryocoolers to the level of 100's of W is needed for filling the gap for this type of machines, as they allow for greatly increasing the cooling efficiency and capacity and while strongly diminishing the required power.
Research Priorities
To achieve the SMES targets given in table 12, R&D efforts are required in the following areas:

1. Improve critical material properties of HTS conductors and MgB$_2$ tapes. This includes higher in-field current densities, lower AC and ramping losses, optimised wire architectures, longer lengths of high-quality, high-amperage conductors, and cost reduction.

2. Develop SMES related system technology with a focus on new concepts in magnet design, standardised components for cooling systems, cryostats, and low loss current leads and power electronics.

3. Develop robust and self-stabilised HTS SMES magnets including high performance electrical insulation with low-cost manufacturing and winding methods. Modular approaches and methods for up-scaling have to be taken into account.

4. Demonstrate HTS SMES system performance in attractive applications with long-term field tests. Business cases need to be further developed and first niche markets need to be addressed.

5. Develop low temperature heat rejection cryocoolers for working between the interval 120–30K with cooling power in the range of 100's of W, able to work with cryogens at 120K or 77K as high temperature, allowing so the use of LCH$_4$, LN$_2$ or LO$_2$ as the first cooling step.

6. Explore the opportunities of hybrid SMES systems at different TRLs depending on the maturity of the hybrid system. This could range from system studies up to first demonstrations.

SMES Recommendations for Research Funding, Infrastructure, and Incentives
Research funding should be focused on closing gaps towards commercialisation and on the research priorities listed above. As an example, improving the cost–performance ratio of HTS material would improve the economic viability of SMES and support the fast rising commercialisation of HTS materials. It is also important to demonstrate SMES performance in lighthouse demonstration applications. This could be for example in a large scale hybrid energy storage demonstrator. Synergies can be exploited by using existing energy infrastructure to integrate a SMES demonstration system like the Energy Lab2.0 at KIT or comparable infrastructure.

Research infrastructure should be expanded and further supported and should enable clustering of research groups in Europe. Furthermore, an effective distribution of efforts between SMES research centres in Europe should be supported, as well as networking between the different disciplines.
### 6.4 Mechanical Energy Storage

#### Compressed Air Energy Storage

**Introduction**

Compressed Air Energy Storage (CAES) refers to a process in which energy is stored in the form of high pressure compressed air. A CAES system can be built to have power scales from a few kilowatts to over a few hundred megawatts and energy charge and discharge durations from a few minutes to a few days with moderate response time and good partial-load performance. Any CAES installation refers to the establishment of a system integrating different interacting components, devices, and processes. The common components of a CAES system must include compressors, expanders, and an air storage reservoir. The rest of the system components depend on the system structure and operation principles.

Successful CAES implementation derives from the mid-20th century. In 1949, S. Laval obtained a patent on using air to store power inside an underground air-storage cavern, which marked a new era of CAES applications. The world’s first utility-scale CAES plant was installed and commissioned to operation by “Asea Brown Boveri (ABB)” at Huntorf, Germany, in 1978. It has a rated power generation of 290 MW. As an available option for peak load shifting in power grid operation and due to its relatively low cost compared to oil and gas prices through the 1980s to 1990s, CAES technology development and its industrial applications have remained attractive. In 1991, another large-scale CAES plant commenced operation in McIntosh, Alabama, USA. The 110 MW plant, with a storage capacity of 2,700 MWh, is capable of continuously delivering its full power output for up to 26 hours. The plant is used to store off-peak power, generate peak power, and provide spinning reserves. The common feature of these two CAES plants is that they all involve burning a fossil fuel – natural gas – in their electricity generation process.

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89 B. J. Davidson, et al., “Large-scale electrical energy storage”

90 Ibid.


91 Ibid.

Maturity of technology
The Huntorf and McIntosh CAES power plants demonstrate the maturity of the first and second generation CAES technology. The current development focuses on the third generation CAES technology which aims to avoid involving fossil fuel by using the heat generated through the compressing process\textsuperscript{93}.

In 2010, RWE Power, General Electric, Züblin and the German Aerospace Centre (DLR) started working on the world’s first large-scale Advanced Adiabatic (AA-CAES) demonstration plant project, in which the heat generated in the compression stage is stored in a thermal storage medium and used at the expansion process\textsuperscript{94}. However, this project was put on hold due to the lack of clarity about its economic and business viability. Meanwhile, some R&D work in small-scale CAES has attempted to use CAES to replace chemical batteries in some applications. US-based LightSail Energy Ltd. patented and developed a CAES technology which came very close to achieving isothermal compression and expansion (I-CAES) and which captures the heat from the compression process by spraying water (with water drop sizes at the nano-scale) for efficient heat absorption and storage. The stored heat is then added to the compressed air during expansion using the same technology\textsuperscript{95}.

A number of demonstration projects are currently on-going, indicating that the technology for CAES with no fossil fuel is available. However, widespread deployment requires market maturity and improvement in round trip efficiency.

Applications
In addition to the existing uses of CAES in Huntorf and Alabama, CAES can also provide a wide range of attractive system services owing primarily to the impressive ramp rates associated with the technology. CAES is capable of providing system services such as, but not limited to, inertial response (in both compression and expansion), operating reserve (primary, secondary and tertiary), fast frequency response, fast post fault active power recovery, dynamic reactive response, and steady state reactive power. CAES’ ability to provide such services will be a key enabler for permitting higher levels of renewable energy and reduce wind power curtailment while maintaining power system stability. A wide range of applications of CAES is outlined in Table 13.

\textsuperscript{94} RWE power, ADELE – Adiabatic compressed–air energy storage (CAES) for electricity supply, ADELE Brochure, 2016. \url{https://www.rwe.com/web/cms/mediablob/en/391748/data/364260/1/rwe-power-aq/innovations/Brochure-ADELE.pdf}
\textsuperscript{95} Lightsail Energy Ltd, 2016. \url{http://www.lightsail.com}
**Table 13 Application potentials of CAES related technology**

<table>
<thead>
<tr>
<th>Application area</th>
<th>Characteristics ([18, 50, 61 ~ 65])</th>
<th>Suitable or potential CAES related technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power quality</td>
<td>&lt;1MW, response time (milliseconds, &lt;1/4 cycle), discharge duration (milliseconds to seconds)</td>
<td>Hybrid systems with small-scale CAES and battery or supercapacitor or other EES technologies with fast response</td>
</tr>
<tr>
<td>Energy management</td>
<td>Large-scale (&gt;100 MW), medium/small-scale (&lt;100 MW), response time (minutes), discharge duration (up to days)</td>
<td>Large-scale energy management (large-scale CAES); Small-scale energy management (small-scale CAES, LAES)</td>
</tr>
<tr>
<td>Renewable back-up power</td>
<td>100 kW–40 MW, response time (seconds to minutes), discharge duration (up to days)*</td>
<td>Multi-scale CAES, hybrid systems with CAES and capacitor or others with fast response may need, possible LAES</td>
</tr>
<tr>
<td>Emergency back-up power</td>
<td>Up to 1 MW, response time (milliseconds to minutes), discharge duration (up to ~24 hours)*</td>
<td>Possible small-scale CAES, hybrid systems with small-scale CAES and other technologies with fast response</td>
</tr>
<tr>
<td>Time shifting</td>
<td>1 MW–100 MW and even more, response time (minutes), discharge duration (3–12 hours)</td>
<td>Multi-scale CAES and LAES</td>
</tr>
<tr>
<td>Peak shaving</td>
<td>100 kW–100 MW and even more, response time (minutes), discharge duration (hour level, &lt;10hours)</td>
<td>Multi-scale CAES and LAES</td>
</tr>
<tr>
<td>Load levelling</td>
<td>up to several hundreds of MW, response time (minutes), discharge duration (up to ~12 hours and even more)</td>
<td>Multi-scale CAES, possible LAES</td>
</tr>
<tr>
<td>Black Start</td>
<td>Up to rated output (depending on stored energy) response time minutes</td>
<td>Multi-scale CAES</td>
</tr>
<tr>
<td>Inertial Response</td>
<td>Provided in both compression and expansion</td>
<td>Multi-scale CAES</td>
</tr>
<tr>
<td>Frequency Response</td>
<td>XX MW – XX MW, range dependent on system operator response requirements</td>
<td>Multi-scale CAES</td>
</tr>
</tbody>
</table>

96 X. Luo, J. Wang, "Overview of the current development on compressed air energy storage", EERA Report, 2016. [http://integratedenergystorage.org](http://integratedenergystorage.org). Not all characteristics outlined in this reference have been included in the table. These are not the only characteristics CAES is capable of providing, as the characteristics are dependent on the system operators’ requirements. Examples have been added to the table.
**SET–Plan targets**

Table 14 lists the theoretically highest achievable efficiency for all the major segments in a CAES system. From the table, it can be seen that the highest efficiency that can be achieved theoretically is 81.9% to date.

<table>
<thead>
<tr>
<th>Efficiency</th>
<th>System Efficiency</th>
<th>Compression Efficiency</th>
<th>Heat storage Efficiency</th>
<th>Cold storage efficiency</th>
<th>Storage efficiency</th>
<th>Expansion Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Theoretical value</td>
<td>81.9%</td>
<td>91%</td>
<td>99%</td>
<td>99%</td>
<td>99.8%</td>
<td>92%</td>
</tr>
</tbody>
</table>

The target should be to achieve the following efficiency by 2030:

<table>
<thead>
<tr>
<th>2016 – 2020</th>
<th>2020 – 2030</th>
</tr>
</thead>
<tbody>
<tr>
<td>Achieving system efficiency of 60 – 65%</td>
<td>Achieving system efficiency around 70%</td>
</tr>
</tbody>
</table>

**Gaps between targets and present performance**

As described above, the main weakness of CAES is its relatively low energy efficiency. From the current large scale CAES (> 1 MW) reported, the best round-trip efficiency achieved is around 53%. The main target for CAES technology development is to improve the CAES system efficiency to reduce the gap between the practical system efficiency and the theoretically achievable efficiency.

**Research Priorities**

To further the development of CAES technology, the following research challenges need to be addressed, in the order of priority from high to low:

1. **Innovation in turbo machinery design and manufacturing:** technical innovations and technology breakthroughs are essential, especially for high-pressure compressor and turbine technologies, such as developing improved sealing methods for compression and expansion machinery to suppress internal leakage and discovering approaches to minimise losses associated with secondary flows in compressors and turbines.
2. **Formation of salt caverns:** Salt caverns for compressed air storage can be developed through solution mining techniques which can provide a low cost and reliable methodology. To make the process economically viable, the process should maximise the size/volume of the caverns for each salt mining well drill. Costs related to the location of the energy source relative to the storage site(s) need to be examined in the techno-economic analysis.

3. **Aboveground manufactured reservoir:** Above ground CAES is possible in steel pipes. However, these systems are currently prohibitively expensive. New materials for these reservoirs, such as carbon fibre or glass fibre, could be the next breakthrough technology which could allow aboveground CAES to compete with the costs of underground CAES. To make this happen, more understanding of fibre meshing or weaving is needed to improve efficiency and reduce costs.

4. **Thermal storage for improvement of round trip efficiency:** The low efficiency of CAES results from the heat losses in the compression and expansion modes, air leakage throughout the whole CAES system, and internal energy losses due to the air compressibility. To improve CAES round trip efficiency, the following research is required:
   i. suitable thermal storage procedure and facility design to maximise the utilisation of thermal energy stored, such as high-pressure thermal storage;
   ii. the individual components or devices working at their optimal status do not mean the whole system is in its optimal status due to complicated coupling effects.

5. **Integrated technologies:** Integrated utilisation of energy through the whole process, e.g. through the coupling of CAES with waste heat or district heating and cooling, can increase the round trip efficiency as the energy losses can be recovered via the integrated process.

**Recommendations for research funding, infrastructure and incentives**

**Research Funding:** The priority should be given to turbo machinery research; that is, efficient large scale compressor and expander technologies as well as high efficient low cost thermal storage technologies. In addition, funding will be required for prefeasibility/feasibility studies to identify optimal locations, plant configuration, system requirements, and business models for CAES facilities.
Infrastructure: it is urgent to provide the essential financial support to complete building CAES plants or to complete projects like the ADELE\textsuperscript{97} one in Germany, so that essential knowledge and experience can be gained from CAES plants construction and operation.

Incentives: favourable policy needs to be in place to ensure that newly built CAES plants are able to maintain their operations. Appropriate regulatory treatment needs to be put in place to ensure that revenues are sufficient to incentivise investment in CAES technology and deployment of CAES facilities.

\textsuperscript{97} RWE power, ADELE – Adiabatic compressed-air energy storage (CAES) for electricity supply, ADELE Brochure, 2016. \url{https://www.rwe.com/web/cms/mediablob/en/391748/data/364260/1/rwe-power-ag/innovations/Brochure-ADELE.pdf}
Flywheel Energy Storage

Introduction
This kinetic energy storage system is composed of a flywheel driven by an electrical machine (different types of technologies are considered, mainly permanent magnets and reluctance machines), able to work as a motor or a generator, and some power electronics to drive the machine, connecting to the electric grid or the load. When the electric machine (acting as a motor) exerts a positive torque $T$ to the flywheel with moment of inertia $J$, it increases its rotation speed at a rate of $T/J$, until it reaches maximum velocity, storing a given kinetic energy and getting power from the grid or the load through the power electronics converter. At this stage the energy can be maintained constant at the flywheel by supplying the idle losses in the machine. To release the energy, the electrical machine (acting as a generator) applies a negative torque $-T$ to the flywheel, braking it at a rate $-(T/J)$ and pumping the energy back to the grid or the load to which it is connected.

Two main groups of technologies are being developed for flywheels: metallic and compound materials. The first are relatively slow (below 10,000 rpm). The wheel is metallic and often has magnetic levitation systems which offset its weight. These slow storage systems are, in theory, simpler in a technological sense. Their main use is in stationary applications, where their weight is not an obstacle.

There is also another family of flywheels: rapid flywheels whose velocity can achieve 50,000 rpm and which use wheels made of composite materials, such as carbon fibres, which offer high levels of mechanical resistance and low density. The elevated cost of the wheel and the difficulty of manufacture mean that its use is restricted in general to applications of limited energy in which the system price is not a critical issue. The greater densities per mass unit are achieved using compound materials (ideally carbon fibre). But if the concern is to achieve energy per volume unit, metals such as steel can be as effective as fibres, while remaining much more economical.

Flywheels are a fast-reacting energy storage technology characterised by high power and energy density, the possibility to decouple power and energy in the design stage, a large number of life–cycles, the possibility to be installed in any location (even on board applications are being considered), and high power but usually low energy compared with some other energy storage devices. Moreover, the operation of flywheels is less dependent on the external temperature than other storage technologies (e.g., batteries). State of charge (SoC) is also easy to determine since it is directly related to the rotational speed. Finally, the dynamic response is fast and not temperature dependent.
**Maturity of technology**
Flywheel is a mature technology, which is completely introduced in the industrial market. More than 20 manufacturers have been identified and many research centres are focused on this technology as well developing prototypes. However, some technological aspects need to be improved both in manufacturing and equipment cost in order to be competitive with other energy storage solutions. Technology Readiness Level (TRL) has reached the maximum level of 9 in some commercial products. However, many alternative solutions or prototypes are situated in the TRL range between 3 and 8.

**Applications**
Flywheels are suited to a number of applications, including:

1. Transportation, which can help reduce CO₂ emissions, increase the efficiency, reduce the power consumption peaks, enable energy savings, and contribute power line voltage stabilisation. Flywheels can be applied in electric and hybrid automobiles (both in electric cars and buses), light trains, underground transportation, and ferries.

2. Supporting the integration of renewable energy generation by contributing to grid stability, frequency regulation, and voltage support.

3. Industry applications, to ensure power supply or increase the efficiency. Flywheels can be applied for cranes and elevators and can serve as a UPS.

A continuous study of the potential applications could reveal new and interesting uses, increasing the industrial market for companies developing flywheels. Moreover, recent research studies have demonstrated that the use of flywheels not substituting but completing the operation of other energy storage technologies, such as batteries, can increase their life cycle (hybrid energy storage).

**Table 15: SET–Plan targets**

<table>
<thead>
<tr>
<th>Current performance</th>
<th>Target 2030</th>
<th>Target 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>High cycle life &gt;100000 cycles</td>
<td>Reduced friction, higher rotation speed for higher energy storage (&gt;10kWh)</td>
<td>Higher energy storage density &gt;100Wh/kg</td>
</tr>
<tr>
<td>Power: 100 – 1500 kW</td>
<td>Stronger materials (composite)</td>
<td>Cost reduction &lt; 350€/kWh</td>
</tr>
<tr>
<td>Energy: 0,5 – 50 kWh</td>
<td>Rotor manufacturing cost reduction &lt;3000 €/kWh</td>
<td></td>
</tr>
<tr>
<td>Roundtrip efficiency: 80–90 %</td>
<td>Large scale demonstration sites</td>
<td></td>
</tr>
<tr>
<td>Cost: 500–3000 €/kWh and 1000–2000€/kW (depending on the power and energy levels)</td>
<td>Development of competitive magnetic bearings</td>
<td></td>
</tr>
</tbody>
</table>
Gaps between targets and present performance
The gaps between the SET-Plan targets and present performance can be broken down across the different parts of the device:

- **Flywheel disc**: developing flywheels with a higher energy density at a lower cost by improving the manufacturing procedure (especially carbon composite and glass fibre flywheels but also metallic) is imperative.

- **Electrical machines**: there is a need for economically reliable manufacturing, a high-quality torque to reduce the bearings requirements, and low machine losses to ensure continuous operation with a simple cooling system.

- **Bearings**: since the system is usually rotating at a very high speed (10,000 rpm) while supporting a high axial force, conventional bearings are not always suitable for use. Magnetic bearing is a widespread technology for high speed systems but more research is still required to ensure robustness and stable operation for use in flywheels.

- **Power electronics**: the speed range of the flywheel is quite large and the machine has to be capable of supplying and absorbing a certain amount of power. A power electronic converter manages the power behaviour of the system, both towards the machine and the electric grid or the load, with a high performance and lowwitching and conduction losses. Moreover, there are additional advantages through using a power converter since it can be used as STATCOM or any other type of grid support, with a minor increase in the complexity and cost.

- **Digital control and communications**: digital control provides a powerful platform to achieve a high performance in fast energy storage systems together with power electronics, enabling the implementation of complex control strategies and a high performance drive.

- **Security case or frame**: the safety conditions of the flywheel must be closely studied, particularly regarding the design of the external case.

Research Priorities
Solving the gaps implies advances for each above-mentioned component:

1. **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.

2. **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.
3. **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\(^98\).

4. **Power electronics**: increase the added value of the power electronics in an energy storage system, ensuring the robustness and reliability and leading to a higher roundtrip efficiency.

5. **Digital control and communications**: digital control and fast communication improvements permit operating the system with guarantees of robustness, being able to analyse a lot of variables, maintaining a complete diagnosis of the application from anywhere, and facilitating integration with other subsystems.

**Recommendations for research funding, infrastructure and incentives**

Funding programmes and incentives should be focused on researching particular technologies involved in flywheels, as well as how to integrate these technologies and test their reliability. Demonstration tests are essential for further investments in the technology. Devices should be tested in demonstration sites where the operation is close to the final application. Programmes and institutions should favour experimental tests in sites such as electric grid areas. Finally, a better knowledge and wider experience in prototypes would reduce the security costs. Research centres and companies should work together to integrate flywheels in facilities where fast energy storage is required in order to test its reliability.

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Liquid Air Energy Storage

Introduction
Liquid Air Energy Storage (LAES), not to be confused with CAES, is an energy storage technology that uses liquid air as an energy vector. The technology benefits from mature supply chains and processes, reducing technology risk. In addition, the technology does not use scarce or toxic components, has a long cycle life, and is well suited for long duration applications.

A LAES system comprises a charging system; up to three energy stores (a main liquid air store, an optional compression heat store, and an optional cold store for high grade cold recovery); and a discharging system. The charging system is an industrial air liquefaction plant where electrical energy is used to reject heat from ambient air drawn from the environment, generating liquid air (“cryogen”). The liquid air is stored in an insulated tank at low pressure, which functions as the main energy store. When power is required, liquid air is drawn from the tank, pumped to high pressure, and evaporated. This produces gaseous air that can be used to drive a piston engine or turbine to do valuable work that can be used to generate electricity. The stored compression heat can be used to increase the work output. Alternatively, (waste) heat from an industrial process, a gas turbine or other conventional power station can be used to heat up the air before expansion. The stored cold can be used to reduce the power consumption of the liquefaction process.

![Figure 12: LAES mode of operation](image-url)
Maturity of technology
The LAES technology concept was first proposed by researchers at the University of Newcastle upon Tyne (UK) in 1977 for peak shaving of electricity grids\(^99\). This work led to subsequent development of the technology particularly by Mitsubishi Heavy Industries and Hitachi (Japan) and Highview Power Storage in collaboration with the University of Leeds (UK). The world’s first demonstration plant (350 kW/2.5 MWh) was built by Highview Power Storage and is currently located at the University of Birmingham Campus and it is the only one that has an actual liquefier for liquid air production (about 30 tons/day capacity). The overall process has been demonstrated by Mitsubishi Heavy Industries Ltd and Highview Power Storage in two pilot scale plants.

Mitsubishi Heavy Industries demonstrated the LAES technology in the late 1990s in a pilot scale with roughly 2 MW power output with an integrated gas turbine system\(^100\). Mitsubishi Hitachi Power Systems Europe and the Linde Group have been jointly developing the LAES technology since 2012. They have successfully developed a “generation 1” system based on commercially available components, thus avoiding the need for lengthy product development, which can be built today. The system can be a stand-alone plant with integrated heat storage or it can be retrofitted to an existing simple cycle gas turbine power plant. The gas turbine can still be operated as a separate open cycle unit without the charging/discharging operation. In this case the plant functions as a pure peaking unit\(^101\). There is also significant integration potential into industrial processes, such as utilisation of waste heat or waste cold to increase the plant efficiency and the flexibility of the industrial process.

Meanwhile, Highview has developed a 5 MW/15 MWh pre-commercial demonstrator connected at distribution level. The plant is located alongside a landfill gas generation plant in greater Manchester and is expected to be commissioned in the second half of 2016. In addition to providing energy storage, the plant will convert low-grade waste heat to power. The project will demonstrate the LAES technology, providing balancing services and supporting the local grid during the winter peaks. The completion of this project will take the technology’s TRL from 7 to 9 as the system will be proven to work in an operational environment.


Additionally, the Birmingham Centre for Cryogenic Energy Storage at the University of Birmingham is currently working to further improve the round trip efficiency of LAES. The main research areas are: development of novel materials for high performance heat and cold storage, development of novel thermodynamic cycles and generation processes, systems integration, control, and optimisation for LAES.

**Applications**

LAES is suitable for many applications, including:

- *Renewables integration*: LAES can support renewables integration by absorbing excess energy, thereby reducing curtailment.

- *Network reinforcement deferral*: LAES can be installed near demand centres, reducing the need to deploy additional cables to serve local peak demand. Storage can act as an alternative or supplement to new transmission and distribution capacity. Using LAES in this application would optimise network asset utilisation as the storage system would charge for most of the night using the network transport capacity when it is less congested, and it would alleviate grid congestion at peak times by providing power at local level.

- *Daily/weekly balancing*: LAES can be used to optimise electricity bills by charging at times of low prices and discharging when prices are high.

- *Security of supply (capacity provision)*: LAES provides flexible peaking capacity. Long duration systems, such as LAES, are able to contribute to security of supply to a greater extent than short-duration storage devices.

- *Frequency control, reserve and other ancillary services*: LAES can contribute to grid stability by responding to imbalances in electrical energy production and consumption. In addition, LAES can provide natural system inertia.

- *Black start*: a LAES system can provide capacity and energy after a system failure (blackout).

- *Improve energy efficiency in LNG regasification terminals*: LAES can harness waste cold from the regasification of liquid natural gas to produce liquid air which is then used to produce electricity, enhancing overall energy efficiency.

- LAES can be used to *increase the flexibility of conventional power plants* by lowering the minimal load and increasing the maximal load due to connections between the thermodynamic processes.
Table 16: SET–Plan targets

<table>
<thead>
<tr>
<th>Current performance</th>
<th>Target 2030</th>
<th>Target 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demonstrated at pilot and pre-commercial scale – 5MW storage</td>
<td>Full commercial scale demonstration – 15 to 50MW /500MWh storage scale</td>
<td>100 MW/GWh storage scale</td>
</tr>
<tr>
<td>Round trip efficiency (RTE) ~20% at pilot scale; 50–60% (predicted) for stand-alone commercial scale LAES; potential of &gt;65% by utilisation of waste heat</td>
<td>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</td>
<td>Round trip efficiency 70%–80% 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</td>
</tr>
<tr>
<td>250–600 €/kWh or 2000–3500€/kW (LAES size dependent)</td>
<td>Cost reduction: 200–400 €/kWh or 1500–2500 €/kW (LAES size dependent)</td>
<td>Mature LAES costs: &lt;200€/kWh or &lt; 1000 €/kW</td>
</tr>
<tr>
<td>Little attention paid on developing new materials and devices for enhanced performance of LAES</td>
<td>Advanced materials &amp; 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</td>
<td>Optimal integration, operation, and management of LAES in low carbon grid environment</td>
</tr>
</tbody>
</table>

Gaps between targets and present performance
LAES extensively uses commercially available components which make the technology positioned near market conditions. However, key components, operating conditions, and costs can be further improved to reach higher performances and provide better business cases. The technology gaps – divided into the different aspects of LAES – are:

- **High investment costs**: there is a need to identify and quantify cost reduction drivers such as modularisation and development of ad hoc components.
- **Round trip efficiency (RTE)**: thermal energy storage materials and systems have to be thoroughly studied and optimised for LAES.
- **RTE**: minimisation of required compression work during charge and maximisation of power output during discharge is crucial to increase round-trip efficiency of LAES.
- **RTE**: an improved purification unit can help improve round trip efficiency of LAES.
• **RTE**: integration of LAES with conventional plants, as it has the potential to increase overall efficiency. Comprehensive integration studies and full scale demonstration should be implemented.

• **Missing optimal operation and dispatching of LAES plants**: complete system analyses and optimal integration with the grid are needed to achieve the best technological benefit, maximise revenues, and improve business cases for LAES.

**Research Priorities**
The following research priorities will be key to support the development of cost–effective LAES technologies:

1. **Intense thermal energy storage (TES)** materials, devices and systems research will be necessary to achieve substantial improvements in storing heat and cold during charge and discharge processes of LAES. Research should be directed at improving cycling operation of TES systems, increasing energy storage density, and minimising costs.

2. **Research should be conducted to maximise performance of cryogenic pumps and compressors for LAES**. Cryo–pumps that can achieve optimal pressure for the LAES discharge process should be sought while solutions for removal and storage of heat of compression should be developed for the compression stages.

3. **Exploratory research on advanced air purification units is recommended**. Removal of CO₂, humidity, Argon, etc. by adsorption phenomena could represent an extra source of heat/cold storage in LAES. However, novel cost effective materials and design should be developed to exploit this opportunity.

4. **Development of novel cycles for the discharge process**. Currently liquid air is directly expanded through turbomachinery to generate power output. Novel indirect combined cycles have the potential of increasing LAES round trip efficiency. In particular, Indirect Rankine cycles with cryogenic fluids such as CO₂, CH₄ and C₃H₈ should be investigated and demonstrated at pilot scale.

5. **Detailed integrated LAES–conventional plants design should be developed**. LAES has the potential to exploit streams of waste heat from conventional power plants and industrial processes. Detailed studies and full–scale demonstration for coal plants, open cycle gas turbines, and diesel generators should be conducted to fully show LAES’s potential and provide business cases.

6. **Best operation and dispatching strategies for LAES plants should be researched**. Optimal integration of LAES into the grid will strongly depend on installation locations, the market framework, and regulation. A lack of tailored
operational strategy could potentially lead to missed revenues and missed technical benefits for the energy system. Thus, a range of operation strategies should be developed for current and future market scenarios anticipating the role of LAES in low carbon grids. Particular attention should be given to the mutual interactions which may arise when LAES integrates with other conventional power plants; as off–design conditions may arise, optimal operations should be sought to achieve maximum benefit from the integrated power generation system. The enhancement of LAES response time through the integration of spin–gen technology could also be studied.

Recommendations for research funding, infrastructure and incentives
LAES requires support and industrial uptake for further technical development and to enhance the market readiness level. Industrial–academic consortia should be supported to design, implement, and operate full–scale LAES demonstrators in multiple technical/economic environments. Strong support for academic research in new materials, components and devices, and novel system configurations will be required to maximise LAES performance and reduce overall costs. Similarly, adequate regulatory aspects and sound market conditions are necessary for the large–scale industrial uptake of LAES.
Pumped Hydro Storage

Introduction
Pumped Hydro energy storage (PHS) is among the most efficient and flexible large-scale means of storing energy available today. This proven technology allows not only to produce electric energy, as hydropower plants do, but also to store it in the form of gravitational potential energy of the water. During periods with high demand or energy high prices, the water, stored in an upper reservoir, is released through turbines to a lower reservoir in order to produce electricity. During periods with low demand or energy prices, the water is pumped back from the lower reservoir to the upper reservoir to store it.

PHS plants require very specific site conditions to be feasible and viable, including proper ground conformation, difference in elevation between the reservoirs, and water availability. The reservoirs are generally located above ground, but some unconventional applications adopt the sea as lower reservoir (seawater pumped hydro energy storage) or underground caverns as lower or, less often, upper reservoir (underground pumped hydro energy storage).

In recent years, pump–turbines have been also operated with variable–speed motor–generators (variable–speed pump–turbines), which enables operation over a wider range of operating conditions by varying the pump–turbine rotation in speed (at the time being ±10 % of the nominal speed). While in generating mode, the variable–speed technology has allowed to reach an operating range comparable to ternary set, while in pumping mode the ternary type still remains more flexible102. This also increases both the flexibility and response time of PHS plants.

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Maturity of technology
PHS is undoubtedly the most mature large-scale energy storage technology. Today, in Europe, this technology represents 99 % of the on-grid electricity storage. PHS has long been the standard solution for peak shifting in Western Europe, where inexpensive nuclear power is used to supply base load demand and to pump water to the upper reservoir of PHS plants during periods of low demand. It is now becoming increasingly common to manage the fluctuations variable RES supply in North Western Europe using PHS.

PHS plants are equipped with hydraulic, mechanical, electrical, and in some cases power electronics equipment, most of which have already reached a TRL of 9 (actual system proven in operational investment). The power of PHS plants ranges from approximately 20 to 500 MW. The most typical values are between 200 and 350 MW, with a storage capacity of 4 to 24 hours at full load for closed-loop PHS and depending on the upper reservoir dimensions for open-loop PHS. PHS plants are generally installed in mountainous or hilly areas where heads of 75–1500 metres can be obtained. PHS holds excellent grid connection properties, as illustrated in table 17 and figure 14, below.

Table 17 – PHS features (VS = variable-speed, TS = Ternary Set)

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


Since conventional PHS plants can only regulate their power in generation mode, their operation in pumping mode is less flexible. Therefore, new technologies are being developed to enhance the operational flexibility of PHS plants\textsuperscript{105}. Although the vast majority of PHS plants installed in Europe are fixed-speed, there is a large potential to convert existing fixed-speed plants (many of which require refurbishment) to variable speed\textsuperscript{106}.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{timeframes.png}
\caption{Timeframes for modern advanced PHS unit regulation\textsuperscript{107}}
\end{figure}

**Applications**

PHS technology can ramp up to full production capacity within minutes, providing a quick response for peak-load energy supply and making it a useful tool for the following services:

- **Provision of contingency reserve to restore the balance of supply and demand:** in generation mode, when one or more generating units of the normal electric supply resources become unavailable unexpectedly. In pumping mode, when there is a sudden drop of load.  
  \textit{Requested response time:} within 10 minutes.  
  \textit{Requested reserve:} generally at least as large as the single largest generation unit.

- **Provision of regulation reserve:** PHS is ready to increase or decrease pumping and generating power as needed and it is used to maintain the grid system


frequency at a narrow band around the nominal value by balancing supply and demand. Frequency response is very similar to regulation but it requires a shorter response time. Since frequency containment or primary control reserve has to be capable of being activated within seconds, normally pumped storage plants cannot be applied unless they are already in operation or they are specifically designed for fast activation times. Requested response time: seconds to a few minutes.

- **Load following**: the PHS provides fast ramping capacity in order to respond to a rapid or randomly fluctuating load profile. Expected up- and down-ramp rate: MW/minute. Timeframe: minutes.

- **Load shifting (energy arbitrage)**: the PHS increases the efficiency of system operation by increasing the generation of base load units and decreasing the operation of expensive peaking units.

- **Black start**: the PHS provides an active reserve of power and energy within the grid. It can be used to energise transmission and distribution lines and to provide station power to bring power plants on line after a catastrophic failure of the grid.

- **Voltage support**: the PHS can generate reactive power to maintain grid voltage within specific limits so as to operate the transmission system in a stable manner.

**SET–Plan targets**

*Table 18 – SET Plan targets for hydro energy storage technologies towards 2030 and beyond*

<table>
<thead>
<tr>
<th>Current performance</th>
<th>Target 2020–2030</th>
<th>Target 2050</th>
</tr>
</thead>
<tbody>
<tr>
<td>GW storage</td>
<td>Materials radical redesign &amp; research on power electronic components</td>
<td>Efficiency improvement</td>
</tr>
<tr>
<td>Low cycle cost high capital cost</td>
<td>Turbine efficiency improvement</td>
<td>Cost reduction</td>
</tr>
<tr>
<td>$500/kW to $2000/kW (350 to 1500€/kW)</td>
<td>Increase regulation capacity in pumping mode</td>
<td>Expand possibilities of PHS installations</td>
</tr>
<tr>
<td>Round trip efficiency 70–80%</td>
<td></td>
<td>Ultrafast regulation</td>
</tr>
<tr>
<td>Primary regulation capacity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Gaps between targets and present performance

The way to operate PHS has changed dramatically following the integration of a large amount of variable generation with an increasing need to provide frequency regulation and therefore for PHS to be operated over a wider range of power and with the shortest possible reaction time. The need for increased flexibility is therefore one key area for development.

Pump turbines must be optimised to provide a wide range of power in generation mode. Variable speed technology needs to be further developed (from ±10% to ±100%) in order to increase the regulation capacity in pumping mode. This will also necessitate developing a new concept of pump turbines able to provide the full benefit of regulation in pumping mode.

In the long term, the introduction of large high voltage DC (HVDC) electric highways combined with the development of a large quantity of generation assets connected through power electronics will create new needs for ultra-fast regulation, requiring PHS units to operate as flywheels, delivering power regulation within milliseconds.

The other major gap between needs and present performance is to reduce the inherent limitation that is PHS’s dependence on geography. Equipping very high head (above ~700m) and very low head (below ~100m) sites remains challenging due to different problems: current multi-stage reversible pump–turbines (RPTs) used above 1000m head do not provide power regulation in generating mode; in low-head sites, the pump–turbine behaviour at part load is affected by too low efficiency in both modes and by unstable operating conditions in pumping mode.

Therefore, very high head pumped storage power plants would require new, economically viable solutions to provide the much needed flexibility: technologies such as variable speed or multiple stages regulated RPT need further developments. This should foster developments for equipment for higher and lower head sites and for upgrading conventional hydro into PHP as well as for new energy storage plant concepts.

Research priorities

Some of the main research priorities for PHS are the following:

1. Increasing PHS flexibility by:
   - Developing a full range variable-speed motor generator (±100%) to allow secondary regulation in pumping mode (suggested target for 2030) and, in
the long term, to allow the PHS units to operate as flywheels and deliver power regulation in milliseconds (suggested target for 2050). Possible synergies between PHS technology and HVDC technology to develop large variable speed solutions with power electronics on the stator should be investigated;

- Increasing the pump–turbine stability during transition between operating modes and at part loads in pumping mode in order to shorten start–up and transition times (from seconds to few minutes) and to favour the exploitation of low–head site. The development of new design criteria for pump–turbines will be necessary (suggested 2030 target).

2. Expanding possibilities for installation of PHS by:

- Developing pump–turbines allowing the upgrading of conventional hydro power plants into PHS while keeping the existing powerhouses to minimise costs and environmental impacts. This will require a new pump–turbine design particularly focusing on the cavitation behaviour to overcome the problems related with the general need of lower foundations in pumping mode (2030 target);

- Studying the development of PHS adopting the sea as a lower reservoir or underground cavern as a lower or, less often, upper reservoir (2050 target);

- For various types of new underground PHS, the development of a standard geology based site selection scheme, including identification and evaluation processes for the different public and industrial stakeholders, is essential. It has to be coupled with a new specialised multi–modal safety operation monitoring concept (2030 target);

- Expanding possibilities to equip more complex sites: going to very high head with the development of multiple stage solutions and very low head with other types of turbines (Deriaz or bulb). Particular application of a low head PHS to investigate will be the Energy Island concept with a reservoir in the sea (2050 target).

3. In a long–term perspective it will be extremely useful to support research on new PHS concepts (e.g. by moving solid mass like soil, gravity power, and bladder reservoir).

4. In order to increase turbine and pump–turbine lifetime, a better understanding of the fluid–structure interactions to limit vibrations coming from hydraulic “turbulences” will be required.

5. Developing standardised mini/micro cost–competitive PHP applications as well as hybrid PHS–wind/photovoltaic applications for centralised/decentralised solutions should be supported.
Recommendations for research funding, infrastructure and incentives
The following table shows the estimated R&D needs for the period towards 2030:

Table 19 – Estimated R&D needs for hydro energy storage technologies

<table>
<thead>
<tr>
<th>Field</th>
<th>Subject</th>
<th>Budget</th>
<th># projects</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flexibility</td>
<td>Full range variable-speed motor generator</td>
<td>3−10M€</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>Wider pump-turbine working range</td>
<td>3−10M€</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>Improved ICT technology: Information, intelligent and interactive</td>
<td>2−10M€</td>
<td>6</td>
</tr>
<tr>
<td>Geographic limitation reduction</td>
<td>More complex sites to equip</td>
<td>2−10M€</td>
<td>11</td>
</tr>
<tr>
<td></td>
<td>Seawater and underground PHS</td>
<td>10M€</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>New plant and reservoir concepts</td>
<td>5−10M€</td>
<td>8</td>
</tr>
<tr>
<td></td>
<td>Upgrade conventional Hydro into Pump Turbine</td>
<td>5−10M€</td>
<td>5</td>
</tr>
</tbody>
</table>

For demonstration and pilot test projects it is estimated that each topic will require a budget in the range of up to several hundreds of millions Euros with a need for funding of about one third.
6.5 Thermal Energy Storage

Thermal energy storage (TES) can be divided into three distinct storage principles: sensible heat storage, latent heat storage, and thermochemical heat storage. These three principles differ in the fundamental way they store thermal energy.

- **Sensible heat storages (SHS)** raise and lower the temperature of a liquid or solid storage medium (e.g. water, sand, molten salts, rocks, with water being the cheapest option) in order to store and release thermal energy for low-temperature applications. This is the most common form of thermal energy storage and has found commercial success on residential and industrial scales.

- **Latent heat storage (LHS)** takes advantage of the energy absorbed or released at constant temperature during a phase change of the material. In most cases, solid/liquid phase change is utilised, with melting used to store heat and solidification used to release heat.

- **Thermochemical heat storage (TCS)** operates in two ways: chemical reactions and sorption processes. In the former, energy is stored as the heat of reaction of reversible reactions. The latter stores thermal energy either through adsorption (physical bonding) or absorption (uptake/dissolution of a material).

In general, thermal energy storage is a cross-cutting technology that will contribute manifold to a future energy system by:

- increasing the share of renewable, **low carbon energies**, especially for solar thermal technologies and with power-to-heat concepts;
- adding **operational flexibility** to (fossil fuel) power plants and industrial processes,
- enabling waste heat recovery in industrial processes, and
- increasing **energy efficiency** in industrial processes and in buildings.

Table 20, below, portrays the complex picture of possibilities for integration of thermal energy storages in different applications. It is important to note that there is no simple 1-to-1 match for technology and application and so far only selected examples of commercially available thermal energy storage technologies are to be found. The definition and values of key performance indicators for TES are highly dependent on the specific application and process benefit could vary from case to case. The following chapters cover each storage principle independently.
Table 20: Applicability of thermal storage technologies for different applications

<table>
<thead>
<tr>
<th>Use and Integration of Low Carbon Energy for Heat Generation</th>
<th>Sensible</th>
<th>Latent</th>
<th>TCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand-driven/stabilising heat supply from local and district heating</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Demand-driven/stabilising heat supply from solar process heat</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Demand-driven/stabilising heat deployment from solar thermal power plants</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Decarbonisation of the residential heating sector using intermittent renewable energy (e.g. wind, solar PV)</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Utilisation of Power-to-Heat concepts</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Combined solar systems</td>
<td>+</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Increasing Energy Efficiency in Industrial Processes</th>
<th>Sensible</th>
<th>Latent</th>
<th>TCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Use of industrial waste heat</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Decoupling of power, heat and cold generation in cogeneration plants</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Increasing Energy Efficiency in Buildings</th>
<th>Sensible</th>
<th>Latent</th>
<th>TCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balancing heat and cold demand</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Decoupling of power, heat and cold generation in micro-cogeneration plants</td>
<td>+</td>
<td>+</td>
<td>0</td>
</tr>
<tr>
<td>Balancing daily demand</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>Balancing seasonal demand</td>
<td>+</td>
<td>0</td>
<td>+</td>
</tr>
</tbody>
</table>

* PLUS (+) Typical/favourable application
** NEUTRAL (0) Possible application

**Sensible Heat Storage**

**Introduction**

Sensible heat storages are the most commonly deployed type of TES. From small residential water tanks to massive molten salt storages in concentrating solar power (CSP) plants or Cowper storages for blast furnaces, all systems operate by the same fundamental principle: increasing or decreasing the temperature of a solid or liquid substance with high heat capacity to store or release thermal energy, transferring the heat directly or indirectly to the process.

Water is a very cost-effective, non-toxic storage medium used at temperatures below 120°C. In combination with solar thermal heating, small, well-insulated storages are commonly built as

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**Figure 15: Crescent Dunes molten salt storage tank**
thermoclines making use of the buoyancy forces leading to thermal stratification. If larger capacities are needed, underground thermal energy storages (UTES) are used. Many types of UTES technologies exist, including aquifer TES, borehole TES, pit TES, and cavern TES, as well as hybrid versions (combined PTES and BTES), which have been piloted and are under development. Steam storage solutions are also promising: some commercial CSP plants implement high pressure steam storage systems, which are useful for a short storage time.

At higher temperatures the most common liquid storage material is molten salt. The salt is pumped between a cold and a hot storage tank for (dis-)charging. In direct systems the salt is used as a storage medium and heat transfer fluid at the same time. Indirect systems employ a heat exchanger with an additional thermal oil cycle. Power and capacity of the storage are thus linked to separate units in the system, heat exchanger and storage tanks respectively. Already highly commercialised, the grid-connected molten salt storage capacity for CSP grew larger than 30 GWth in 2015.

Storage temperatures up to 1000°C are mainly realised by regenerator-type storages transferring the heat from a gaseous medium directly to the solid storage material such as ceramic bricks, natural stones or beds of smaller particles. Similarly, heat generated using resistive elements in Smart Electric Thermal Storage Heaters (SETs) is conducted into a low-cost ceramic brick storage medium and stored at temperatures up to 700°C. The key characteristics of these storage technologies are depicted in table 21.

![Figure 16: aerial view of Crescent Dunes molten salt storage (Source: COBRA)](image)

Table 21: Characteristics of low/high temperature sensible energy storage technologies

<table>
<thead>
<tr>
<th></th>
<th>UTES</th>
<th>LT–storage in liquids</th>
<th>HT–storage in liquids</th>
<th>HT–storage in solids</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy density in kWh/m³</td>
<td>15 – 80</td>
<td>60 – 100</td>
<td>75 – 200</td>
<td>75 – 150</td>
</tr>
<tr>
<td>Feasible size</td>
<td>Up to 15 GWh</td>
<td>Up to 1000 MWh</td>
<td>350 – 4000 MWh</td>
<td>1000 MWh</td>
</tr>
<tr>
<td>Cost per kWh</td>
<td>0.1 – 10 €</td>
<td>0.4 – 10 €</td>
<td>20 – 70 €</td>
<td>15–40 €</td>
</tr>
</tbody>
</table>
Maturity of Technology

Many sensible heat storage technologies have been in development for decades. This is especially true for low temperature water storages whereby small-scale, single-home storages for solar thermal heat are commercially available products (TRL 9). Larger storages for district heating are on a demonstration level or industrially used for heating plants (TRL 8–9). Underground thermal energy storages are commonly used in Denmark, Sweden, The Netherlands, and Norway for seasonal storage of heat in centralised and distributed energy systems. In these countries UTES is applied together with renewable solar or geothermal heat and electricity from photovoltaics in combination with district heating (TRL 9), whereas in other European countries they are still on a demonstration and pilot level.

Far fewer examples are available of thermal energy storages at higher temperature levels. Molten salt storages have become the standard solution for dispatchable solar thermal electricity generation and have reached high TRL levels for this application (TRL 9). However, in other industrial applications they are not yet commercially available (TRL 4–6). The same is true for regenerator-type storages which are commercially deployed in steel and glass industries for waste heat recovery. Usage in power plant engineering is underway but pre-commercial (TRL 6–7).

In contrast, thermal energy has been stored within ceramic bricks at temperatures up to 70°C in residential storage heaters since the mid-20th century. Modern versions of these appliances, SETs, are commercially available and are being used to store vast amounts of thermal energy across tens of thousands of residential properties. With their advanced ICT and communication networks, these SETs are also delivering services, such as demand side management and frequency response, to the electricity industry, enabling it to increase the penetration of low carbon energy sources (e.g. Wind and PV) at both a local and national level. The advanced ICT in SETs is also enabling them to learn their environment and adapt their levels of stored thermal energy for maximum efficiency.

Applications

Sensible heat storage applications include:

- **District heating**: TES systems providing balancing demand and supply services on an hourly, daily or seasonal basis. Technologies applied are UTES, tank, and pit storages.
- **Single-home storage systems**: low-temperature solar heat of up to 40 m³ for high solar shares.
- **Concentrating solar power**: molten salt technologies have been extensively deployed in CSP applications for storage of thermal energy prior to steam or electricity generation. This usage allows CSP plants to generate highly
dispatchable electricity from renewables.

- **Power-to-Heat**: molten salt storages offer potential for conversion of electrical energy to thermal energy. Power to heat is also used for applying heat pumps together with UTES from residential to larger scale level.

- **Power plants**: grid-balancing opportunities emerge from improved operational flexibility. Both regenerator-type heat storages and molten salt storages are applicable in these cases.

- **Industrial processes**: sensible storages are used for increased flexibility and energy efficiency for the glass industry, metallurgy, cement production, steel production, etc...

- **Waste–heat usage**: within industry is also an emerging application, but still pre-commercial.

- **Steam accumulators**.

- **Cowper storage**.

- **Advanced adiabatic compressed air energy storage (AA-CAES)**: AA-CAES employs sensible storages to increase the efficiency in the storage of electricity. AA-CAES systems themselves have a wide range of applications including grid balancing and power plant solutions.

### SET–Plan Targets

There is a specific action on “next generation of sensible thermal energy storages” which is shown in the following table.

<table>
<thead>
<tr>
<th>Target description</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Significantly reduced heat losses and increased energy efficiency</td>
<td>n/a</td>
</tr>
<tr>
<td>Efficient charging and discharging characteristics</td>
<td>n/a</td>
</tr>
<tr>
<td>High flexibility for building integration</td>
<td>n/a</td>
</tr>
<tr>
<td>Reduction of mass-produced containment costs by 20%</td>
<td>n/a</td>
</tr>
<tr>
<td>Containment of 1000L tank (excl. insulation and VAT) of 300 – 700€</td>
<td>2020</td>
</tr>
<tr>
<td>Development of innovative modular concepts</td>
<td>n/a</td>
</tr>
<tr>
<td>Durability and lifetime predictions in the high-temperature sector (e.g. corrosion, thermomechanical issues)</td>
<td>n/a</td>
</tr>
<tr>
<td>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</td>
<td>n/a</td>
</tr>
<tr>
<td>Drastic cost reduction by means of the use of cost-effective storage materials and concepts</td>
<td>n/a</td>
</tr>
</tbody>
</table>
Other targets relevant to sensible heat storage include:

<table>
<thead>
<tr>
<th>Target description</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Development of molten salts to enlarge maximum operating temperature up to 700°C up to TRL 6–7.</td>
<td>n/a</td>
</tr>
<tr>
<td>Reduction of the minimum operation temperature of salts to avoid large tracing energy needs.</td>
<td>n/a</td>
</tr>
<tr>
<td>Development of thermocline–filler molten salt storage system with reduced CAPEX of 25% up to TRL 7–8</td>
<td>2020</td>
</tr>
<tr>
<td>Development of alternative molten salt tank designs with reduced CAPEX up to TRL 7–8</td>
<td></td>
</tr>
<tr>
<td>75% energy efficiency of UTES</td>
<td>2020</td>
</tr>
<tr>
<td>Cost of high-performance insulation reduced below 100 €/m³</td>
<td>n/a</td>
</tr>
<tr>
<td>Develop innovative fluids such as gaseous heat transfer fluids (air, super–critical CO₂ etc.)</td>
<td>n/a</td>
</tr>
</tbody>
</table>

**Gaps in Research**

The advancement of Power–to–Heat applications (from residential scale to power plants and industrial process heat) requires solutions for the direct electrical heating of all types of thermal energy storage. Additionally, research should be conducted on the adaptation of TES technology for its use both in power plant and industrial process heat applications. A combination of TES technologies should be pursued in order to address specific process needs (e.g. steam storage, daily and seasonal storage services in district heating systems). Research is needed to develop and demonstrate smart and flexible heat systems by integrating (underground) thermal energy storage, demand response, smart operation and control techniques. This is needed from the residential scale towards industrial scale, including district heating networks. In addition, due to the diversity of high–temperature TES technologies, potential cross–sectorial technology transfer should be addressed by case studies. There is also a very important research gap on materials: the development of new storage/heat transport fluid materials is a priority in order to provide a successful sensible TES solution.

**Research Priorities**

The main research priorities are:

1. Cost reductions of regenerator–type storages: key to the profitability of sensible heat storage systems, particularly high–temperature and pressurised vessel, is the development of low–cost materials. In particular, waste materials from industry and natural rocks are a promising opportunity for use in TES processes. Carbon fibre tanks are also promising for pressurised vessels. Scale–up of regenerator–type storage technology will also contribute to expenditure decreases. An adapted storage design should be pursued for respective process requirements including up–scaling and materials selection.
for cost reduction.

2. Increases in reliability, system lifetime, and process integration of high-temperature storages: projects on high-temperature process integration of steel, building material, and glass industries as well as power plant processes (improvement of flexibility for grid support).

3. Research in the area of power-to-heat technology with high-grade heat utilisation.

4. Research on novel high-temperature TES concepts for cost reduction or improved operation in system (e.g. thermocline/filler of molten salt storage, solid particle concepts).

5. Materials development for molten salts but also other materials for sensible TES. Molten salt material development should focus on the expansion of the temperature range through the development of new mixtures of molten salts. Active research is being done on new sensible TES material alternatives, investigating both the storage media and the transfer fluid. This includes new, low-cost materials alternatives such as materials coming from industrial waste and, on the fluid side, ionic liquids and gaseous fluids (air, pressurised CO₂ etc).

6. For UTES, there is a need to assess the potential and suitability of the subsurface in Europe. Further there is a need for research and demonstration regarding high temperature storage systems (≥100°C) and hybrid UTES systems to increase capacity, efficiency and alignment with renewable heat production technologies (solar heat, geothermal heat, biomass heat).

7. Molten salt fundamental research: clarification of metallic corrosion and nitrate salt chemistry aspects in the upper temperature ranges. Joint research efforts are recommended in the fields of applied research and materials institutes focusing on mineralogy (e.g. natural stones), molten salts, metallic corrosion, and high temperature free-flowing particles.

Recommendations for Research, Funding, Infrastructure and Incentives
There is a diversity of high-temperature TES options with different maturity levels. For high-temperature TES, funding should be directed towards a direct high-temperature TES funding frame. This would enable to full technology transfer potential of high-temperature TES as a cross-sectional technology.

With respect to cost reductions for regenerator-type storages, funding should be made available to make an effective valorisation process of low-cost materials (e.g. steel slag). This view is aligned with a commitment to a “Circular Economy” with a cross-sectorial added-value approach. This approach has also been suggested in the
European Parliament’s Briefing on the EU Heating and Cooling Strategy\textsuperscript{108}. Additionally, costs can be reduced through thermocline approaches for molten salt storage systems in combination with solid filler materials.

For the concentrating solar power (CSP) application, it will be important to convince decision makers to demonstrate novel TES technologies at a relevant scale. Hence, funding of pre-commercial plants including novel high-temperature TES systems is recommended. Small- to medium-scale European demonstrations and pilot programs should be established with a focus on increased flexibility of industrial processes through heat storage integration. Such activities will be necessary to make the processes compatible with Power-to-Heat techniques fed from fluctuating electricity in the mid- to long-term.

It is recommended to further demonstrate smart and flexible heat infrastructures by integrating seasonal thermal energy storage, energy carrier coupling (Power-to-Heat), demand response, and smart operation and control into existing district heating networks in Europe. Funding estimate: €4–8 million per project.

Latent Heat Storage

Introduction
Latent heat storage (LHS) can be divided into direct and indirect systems, both of which provide critical solutions to the storage of latent heat. Direct systems facilitate heat transfer through immediate contact between the heat transfer fluid (HTF) and the LHS material. Indirect systems separate the HTF and storage material with a solid heat transfer border, in which case heat can either be delivered to a container filled with phase-change material (PCM) or an encapsulated material. In the first case, heat transfer occurs by way of pipes, finned tubes or flat-plate exchangers. Concerning encapsulated PCM, the material is separated in small packages which are then put in contact with the heat transfer fluid. The form of the encapsulation depends on the application and can be found in both stationary and mobile applications.

LHS provides the possibility to store a large amount of heat at a constant temperature, the so called phase-change temperature, making it ideally suited for applications that do not provide or allow for big temperature differences. Accordingly, each system requires a PCM whose phase-change temperature lies in the range of the application. PCMs are available in a broad temperature range. For low temperature storages, water (ice storages) and aqueous salt solutions (for temperatures below 0°C) have been commercialised and deployed on a large scale. Below 100°C, systems have also been created based on salt hydrates and paraffin waxes. Research is also being performed on systems for fatty acids (15 – 70°C), sugar alcohols (90 – 200°C), metal (metal alloys), and salt (mixtures) for temperatures above 200°C.

A key application for high-temperature storages is systems which use steam as a working fluid as well as condensation and evaporation for absorbing and releasing heat. Depending on the working pressure, storage materials with a melting temperature between 150°C and 330°C are required. Due to cost considerations, nitrate salts and eutectic salt mixtures (i.e. mixtures of two or more salts that have a lower melting temperature when combined than when separated) are normally the main candidates. However, metals have also revealed an attractive potential in this temperature range and higher.

The key characteristics of these various storage technologies are depicted in table 22.

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109 However, the cost of the material is not the only aspect determining the overall cost. A significant thermal improvement due to enhanced thermal properties of another material could reduce other related costs, making another technology attractive.
Table 22: Characteristics of LHS technologies

<table>
<thead>
<tr>
<th></th>
<th>LT latent heat storage</th>
<th>HT latent heat storage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy density in kWh/m³</td>
<td>80 – 110</td>
<td>90 – 100</td>
</tr>
<tr>
<td>Feasible size</td>
<td>10 kWh – 2.5 MWh</td>
<td>10 kWh – 10 MWh</td>
</tr>
<tr>
<td>Cost per kWh</td>
<td>0.4 – 10 €</td>
<td>20 – 70 €</td>
</tr>
</tbody>
</table>

**Maturity of Technology**

The development of latent heat storages depends largely on its temperature range. Many low-temperature products using latent heat technology in buildings, mini-storages for foodstuffs, and cooling for medication have been commercialised (TRL 9). Ice storages and aqueous salt solutions (<0°C) have also found large-scale deployment. Salt hydrate and paraffin wax systems are partly commercialised (TRL 6–8). High-temperature LHS with integrated finned-tube heat exchangers have been constructed and operated with variable phase-change temperatures between 140°C and 305°C. These HT storages have reached a TRL of 7. High-power systems remain in research and development with some demonstration projects (TRL 4–5), whereas high-energy storages are TRL 5–7.

While commercialised for ice production for many years, only three laboratory-scale prototypes of high-temperature active latent heat storages have been built to date which are capable of separating the thermal charge and discharge power from capacity and load condition of the storage (TRL 3–4). In the future, LHS with controllable heat transfer power will be necessary for easier integration into many processes. Such controllable active LHS currently do not exist.

**Applications**

LHS applications include:

- Use of waste heat (power plants and industrial processes, vehicles, etc.): due to their isothermal phase change behaviour, high-temperature LHS interact very well with processes where the heat transfer medium also undergoes a phase change. For example, they can be integrated in subcritical steam cycles for process heat.

- Storage of renewable heat: within concentrating solar power plants with direct steam generation in the solar field, high-temperature LHS facilitates a temporal separation from the solar radiation. In this application, LHS enables
higher power plant efficiencies compared to other storage technologies because of their isothermal behaviour. Low-temperature LHS can be used for solar thermal heating systems in buildings. In this application, smaller storages with higher storage densities than water tanks can be realised.

- Cold applications (central storages): the phase change of water at 0°C is used for storage of cold for air conditioning and supply of process cold. Ice storages also serve as a heat source of heat pumps for space heating.
- There are a wide variety of building applications for LHS.
- Stabilising temperatures of sensitive goods (e.g., pharmaceuticals) during transport.
- High-temperature LHS can be integrated in subcritical steam cycles.
- LHS is also being developed for solar thermal power plants in order to facilitate a temporal separation from the solar radiation.
- LHS can be deployed to improve dynamics in steam power plants as well as to reduce partial load and start-up losses. In cogeneration plants, LHS can provide steam generation during revision of turbines or unscheduled interruption of operations.
- In the process industry, LHS increases energy efficiency through improved use of waste heat as well as balancing intermittencies between the availability and demand of thermal energy.
- In the future, LHS can be part of location-independent storage systems for nearly-isentropic Power-to-Heat-to-Power (P2H2P) energy storage. Promising solutions based on right- and left-handed thermodynamic cycles with phase change of the working fluid need LHS for a minimum of exergy loss and so a maximised round trip efficiency.

<table>
<thead>
<tr>
<th>SET–Plan Targets</th>
<th>Year</th>
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<tbody>
<tr>
<td>Improved materials and systems for TES with PCM in buildings</td>
<td></td>
</tr>
<tr>
<td>Specific investment cost of latent heat storage reduced below 50 €/kW</td>
<td>2020</td>
</tr>
<tr>
<td>Increased storage density and thermal transport properties for PCM systems</td>
<td></td>
</tr>
<tr>
<td>Development of microencapsulated PCM for 300 &lt; 1000°C</td>
<td></td>
</tr>
<tr>
<td>Novel PCM development with adjustable phase-change temperature</td>
<td></td>
</tr>
<tr>
<td>Heat exchangers which also encapsulate the PCM</td>
<td></td>
</tr>
<tr>
<td>Latent heat storage with stable and controllable discharging power</td>
<td>2020</td>
</tr>
<tr>
<td>Separation of power and capacity through active heat exchangers</td>
<td></td>
</tr>
</tbody>
</table>
Gaps in Research
Today no LHS with stable and controllable discharging power is available. Due to technical simplicity, almost all LHS today contain passive heat exchangers which do not allow for the separation of capacity and power. Research and development on active heat exchangers with controllable heat transfer power urgently needs to be undertaken in order to overcome these two disadvantages and to prepare LHS for a broad market.

Deep material related research for LHS is vital to improve the thermal properties of PCMs, e.g. thermal conductivity, and to ensure appropriate control of the phase change. Additionally, system storage density of LHS could be drastically increased by using the same PCM not only for latent but also for sensible heat storage (so-called extended PCM). R&D on system and material level needs to be undertaken to achieve SET-Plan Targets on storage density. Furthermore, there are multiple Power–to–Heat applications, e.g. time flexible supply of process steam generated by decentralised photovoltaics (low electrical power) or grid stabilisation (high electrical power) which require R&D work on the efficient integration of electrical heaters into LHS. Finally, a general reduction of specific investment costs requires R&D on the efficiency of heat conduction structures installed inside the LHS.

Research Priorities
There are several key areas of research for LHS:

1. Development of active LHS with stable and controllable discharging power: in order to prepare thermal energy storages with phase change for a broad market, a main focus of future development activities must be the general controllability of the thermal charge and discharge power as well as the independency of the power from the load condition of the storage.

2. Development of LHS with reduced temperature difference between charging and discharging through improved heat transfer: this is mainly important for nearly-isentropic P2H2P energy storage but also affects many other applications where exergy losses are undesirable. Research should address active LHS as well as passive LHS with additional and improved heat conduction structures.

3. Development of active LHS for separation of power and capacity: future LHS must offer the possibility to choose them by power at a distinct temperature difference and capacity independently. Therefore the heat transfer area and volume of storage material must be decoupled, for example by heat exchangers that are separated from the storage tank.
4. Development of systems using the same PCM for latent and sensible heat storage (extended PCM) in order to increase storage density. Material development of PCM with distinct melting temperatures, melting enthalpy, specific heat capacity and relationship between melting enthalpy and specific heat capacity adjusted to various heat transfer fluids and specific processes is needed.

5. Encapsulation of PCM as well as embedding in porous structures: encapsulation of PCM offers the opportunity to use materials with advantageous thermophysical behaviour but problematic properties like toxicity and corrosivity. Encapsulated PCM can be directly brought in contact with the heat transfer medium and so improve heat transfer.

6. Cost reduction: existing LHS technologies need to be reduced in material expenditure in order to transfer technological advantages into cost-related advantages. This includes mainly the heat transfer structure and the containment but also the PCM itself.

Recommendations for Research Funding, Infrastructure and Incentives
The development of LHS with stable and controllable discharging power as well as the separation of power and capacity first need fundamental research in order to understand and quantify the heat transfer processes of active heat exchangers. As this functionality is the key to prepare LHS for a broad market and the research on it is the foundation for further developments, fundamental research projects should be funded in a first step (approximately 3 projects at €1.5 million), particularly with a focus on materials research to improve storage capacity, transport properties, customisation of phase change temperature, latent heat, etc. A next step could be the development of active heat exchangers in research/industry cooperation projects.

Demonstration of systems using the same PCM for latent and sensible heat storage (extended PCM) and the resulting benefits (e.g. increase in storage density) should be undertaken by co-funded integration of pilot storages into real applications. However, such demonstration projects should be accompanied by fully funded fundamental research on material development to adjust the phase change temperatures and the specific heat capacity to specific applications. The development of improved heat conduction structures and encapsulated PCM should be undertaken in projects co-funded by industry and the public sector.

Thermochemical Heat Storage

Introduction
Thermochemical systems (TCS) stockpile heat in two distinct ways: chemical reactions and sorption processes. Thermochemical reactions based on gas–gas or gas–solid
reactions use thermal energy to dissociate compounds (“AB”) into two reaction products (“A” and “B”). Upon subsequent recombination of the reactants, an exothermic reverse reaction occurs and the previously-stored heat of reaction is released. This allows for the theoretically lossless storage of thermal energy. The product “AB” represents a renewable form of thermal energy storage which enables a temporally and spatially independent, reversible thermal cycle.

Gas–solid reactions take place at a constant temperature for a given vapour pressure. This allows TCS to adapt to specific applications through both the selection of the reactants as well as the selection of the reaction conditions. Additionally, due to the dependency of the gas–solid reaction temperature on pressure, the temperature level of the storage can be adjusted by varying the pressure. This means that TCS may provide a higher discharging than charging temperature, otherwise known as a “thermal upgrade”. Another advantage of TCS is the independent sizing of power and capacity – the reactor determines the power while the reactant container governs the storage capacity. TCS based on reactions are currently in the early stages of their development but represent a promising thermal energy storage solution.

Sorption processes can also be used to absorb and release heat through adsorption (physical bonding) and absorption (uptake/dissolution of a material). In adsorption, the reactants (e.g. zeolite and water) are separated during charging and the heat of reaction is released after recombination. The sorption principle can be applied for thermal energy storage as well as for chemical heat pumps. Whereas sorption heat pumps are commercially available, sorption–based thermal energy storage with discharging cycles of more than 1 hour are still in research and development.

The key characteristics of these storage technologies are depicted in table 23.

<table>
<thead>
<tr>
<th></th>
<th>Chemical Reactions</th>
<th>Sorption Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Energy density in kWh/m³</td>
<td>100 – 400</td>
<td>120 – 250 kWh/m³</td>
</tr>
<tr>
<td>Feasible size</td>
<td>System-dependent</td>
<td>2 – 4 MWh</td>
</tr>
<tr>
<td>Cost per kWh</td>
<td>Target: 10 – 90 €/kWh</td>
<td>10 – 130 €</td>
</tr>
</tbody>
</table>
Maturity of Technology

Currently, thermochemical heat storages remain largely in the research and development phase. With respect to systems based on chemical reactions, 95% of installed systems are in R&D and have reached a TRL of 3–4. Sorption storage systems are slightly more developed (TRL 5–7) with the exception of sorption heat pumps which have been fully commercialised. (TRL 9). One of the main reasons for the different TRLs is related to the materials cost. Since continuously operated heat pumps utilise the thermochemical effect at frequent intervals, elaborate materials can be afforded. On the contrary, storage applications require materials available at low cost that are in most of the cases much more complex to handle.

Applications

As mentioned in earlier parts of the TES section, many TES technologies cover the same applications. TCS can also serve applications which are supported by sensible and/or latent heat storage.

The following applications are relevant for TCS:

- Solar thermal power plants
- Industrial process heat (heat transformation)
- Building engineering
- Automotive thermal management
- Seasonal storage and peak-shifting
- Industrial waste heat
- Buffer storage in district heating
- Domestic heating, cooling and hot water applications

However, it is important to understand TCS not as substitute for sensible or latent heat storages. The thermochemical principle rather broadens the range of potential applications for thermal energy storages due to some specific characteristics, including:

- Switchable and controllable release of thermal energy
- Long-term storage possibility
- Adjustment of temperature levels
- Combination of thermal energy storage and heat pumping effects (e.g. cooling)
• Combination with atmosphere control (e.g. dehumidification) and thermal energy storage and so forth
• Consequently, thermochemical storages (or systems) could be seen as thermal process technologies rather than thermal energy storages.

**SET–Plan Targets**

<table>
<thead>
<tr>
<th>Target description</th>
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<tbody>
<tr>
<td>Development of novel or improved thermochemical materials (TCM)</td>
</tr>
<tr>
<td>Improved materials and systems for TES with TCM in buildings</td>
</tr>
<tr>
<td>Development of testing and characterisation techniques for TCM</td>
</tr>
<tr>
<td>TCM should be 4–times more compact than water at system level</td>
</tr>
<tr>
<td>Specific investment cost below 50 €/kWh</td>
</tr>
<tr>
<td>Increased system storage density for TCS</td>
</tr>
<tr>
<td>Identification of niche applications for TCS</td>
</tr>
<tr>
<td>Materials research focused on ensuring an appropriate reaction reproducibility in medium–large term operation.</td>
</tr>
<tr>
<td>Development of appropriate storage concepts in order to maximise the reaction rates, heat transfer, and reproducibility of the reaction.</td>
</tr>
</tbody>
</table>

**Gaps in Research**

There remains fundamental material research to be done in TCS that is unaddressed by the SET–Plan targets. To begin with, the cycling stability of the bulk material must be improved as well as the expansion of the reactive material. Despite the necessity of material research, one of the largest gaps in TCS research is the focus on material rather than reactor and system aspects. In order to raise the TRL of TCS and ultimately create a commercialised product, attention needs to be refocused from material aspects onto reactor aspects. This is somewhat reflected in the SET–Plan targets (e.g. increased system storage density), however these targets remain primarily focused on material development. Efforts should also be made to combine reactive and sorption storages. Finally, a gap in research is the integration of TCS systems in relation to energy system integration: for example, small scale TES on residential level in combination with solar heating and electric heat pumps.

**Research Priorities**

As discussed above, the main challenge for this technology is the transition from material research aspects to system aspects, like reaction control, reactor design and process integration. Therefore, research should focus on inter–disciplinary aspects of the technology, such as:

1. How does a material react in prototype scale in comparison to the mg–scale normally used to determine material properties?
2. What are the potential efficiencies in a real environment in comparison to prototypes operated in lab-scale?

3. Besides these effects related to increase of the TRL, following concrete research aspects are crucial for the technology of thermochemical storages:

4. Development of adjustable and simplified reactor concepts

5. Improved integration of gaseous reactants

6. Selection and advancement of the storage material – thermodynamics, kinetics, cycling stability

7. Optimisation of complete reversibility, reactor design, cost of reactants as well as reactor lifetime (e.g. corrosion issues), sizing and cost improvement

**Recommendations for Research Funding, Infrastructure and Incentives**

The development of TCS with stable and controllable discharging power as well as the separation of power and capacity first needs fundamental research in order to understand the superimposed processes of reaction/sorption as well as heat and mass transfer. As this functionality is the key to prepare TCS – independent from the application or the temperature level – for a broad market and the research on it is the foundation for further developments, fundamental research projects should be funded in a first step (approximately 3 projects at €1.5 million). However, comparable efforts are necessary for fundamental but application-oriented research projects to close the gap between material development on one side and reactor integration and design on the other. Funding of relatively high TRL applications of relatively small scale and modular TCS for buildings and dwellings towards market implementation is needed. Demonstration of TCS as part of integrated systems (e.g. with solar heaters and heat pumps) is also required. These projects are of the highest importance to continuously push the state of development in order to derive guidelines for specified fundamental research.

The deployment of energy storage technologies in Europe does not depend on the strength of R&D efforts alone. An enabling regulatory environment that allows energy storage to compete on an equal basis with other flexibility providers will be essential to sustained growth in the energy storage industry.

As alluded to at the end of Chapter 4, the regulatory framework at EU and Member State level has not evolved to support the cost-efficient deployment of energy storage. At the moment, a fair market design is lacking for energy storage systems. This chapter posits policy recommendations for addressing some of the key regulatory barriers to energy storage deployment which currently exist in the market.

7.1 Policy Recommendations

A first set of EASE policy recommendations has been addressed by the European Commission’s proposed regulation on the internal market for electricity\(^{110}\), as well as the proposed directive on common rules for the internal market in electricity\(^{111}\), issued in November 2016. It is now the role of the European Parliament and the European Council to enshrine these texts into community law and to complement them with the principles below, so as to remove the remaining regulatory barriers hampering the large-scale deployment of energy storage in Europe.

**Recommendation 1:**

**Establish a definition of energy storage in the EU regulatory framework**

(e.g., an amendment to the Electricity Directive)

A robust and broad definition is needed to create investment security for the European industry. It must be clarified if cross-sectorial interfaces, e.g. electricity in and heat, gas or fuel out, can be considered as energy storage or not. To include this would allow the dynamic operation of the electricity grid with thermal, fuel or gas as flexibility for downward regulation, while making the renewable energy from the electricity sector available for the decarbonisation of other sectors.

The definition should reflect all types and applications of energy storage and not only traditional technologies and uses, such as pumped hydro storage or batteries, in order to allow for the development of new technologies. The same reasoning applies to the applications energy storage may fulfil. A narrow view of the applications will restrict energy storage to some limited applications, while a broader view will allow

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a myriad of applications to develop according to technological development and system needs.

In this context, EASE broadly supports the definition of energy storage proposed in the draft Electricity Directive:

“’energy storage’ means, in the electricity system, deferring an amount of the electricity that was generated to the moment of use, either as final energy or converted into another energy carrier.”\(^\text{112}\)

However, EASE proposes to replace the word “generated” with the word “produced”, since an Energy Storage definition is not the place to address the question of ownership (by defining energy storage as generation). Therefore, the definition should read:

“’energy storage’ means, in the electricity system, deferring an amount of the electricity that was produced to the moment of use, either as final energy or converted into another energy carrier.”

We believe that this definition is general and robust enough to establish the concept firmly under European law. Specific, context related clarifications could emerge to resolve precise points, where needed.

**Recommendation 2:**

Establish clarity on the rules under which energy storage can access markets – in particular, the perceived inability of transmission system operators (TSOs) and distribution system operators (DSOs) to own and operate energy storage.

The following is a position that EASE has developed regarding the ownership of energy storage devices:

- One cannot talk about ownership of energy storage by regulated entities in the abstract; instead, positions can be expressed only relative to energy storage applications, or services.

- For energy storage applications deemed to be market services, e.g., arbitrage, only market players should be allowed to own or operate energy storage facilities for their provision. The market should reflect the system needs, which would provide for efficient solutions.

- Energy storage applications deemed to be infrastructure services, i.e., fulfilling services which are today already used by regulated entities with other

technologies (e.g., by building a line), should be able to be delivered also with energy storage devices.

- Regarding the ownership of energy storage by regulated entities (e.g., for the provision of system services) in the absence of competitive supply, i.e. if shown that a market-based service procurement is not feasible, such ownership should be exceptional and on a temporary basis, subject to a periodic review of the situation. Unjustified market barriers for energy storage should be removed.

- And, as a general rule, regulated entities could be allowed to own energy storage in this context only upon the approval of the relevant national regulatory authority (NRA). In the longer term, the underlying reason for the market failure should be identified and properly addressed.

This point is also addressed in the draft directive on the internal market for electricity, but EASE believes that a regulated entity should not be banned from owning energy storage devices in order to fulfill services that are already provided by this regulated entity. As an example, to bring electricity from point A to point B a TSO is allowed to build a line; in fact, the TSO’s only choice to increase capacity is to build a second line. EASE believes that the capacity of the first line may be increased by allowing the TSO to own an energy storage device for this specific service. National regulatory authorities should address the question of whether TSO or DSO ownership of energy storage devices would be economical and could trigger innovative business models.

**Recommendation 3:**
Eliminate unwarranted/double charging, in particular the application of final consumption fees to energy storage given that it does not constitute final use of the energy

Energy storage is not a load, it is storing energy for later use in the grid (e.g., providing transmission or distribution services, peak capacity or other ancillary services). In this context, energy storage assets should not be allocated consumption/demand charges at transmission and distribution levels. This is also valid for network charges and for any kind of taxes that consumers/load would have to pay.

Since this point is not addressed clearly in the above mentioned texts, it falls to the European Parliament and the European Council to make sure that the laws of physics, meaning a kWh can only be consumed once, are reflected in the legal framework, meaning a kWh cannot be taxed twice as a consumer.
Recommendation 4: Ensure the procurement of all energy and ancillary services is market-based

System services are not all procured on market based conditions in all EU Member States. This creates a higher cost for the consumer and discriminates against technologies that are not allowed to provide these services, even if the services would be provided cheaper and more accurately.

In Italy, for example, the procurement of frequency control response (FCR) is not market based. This, therefore, increases the costs of these FRC services for the consumer. A study quantifying these costs found that a given Italian coal plant would save €1.7 million per year by providing the service with energy storage, such as batteries. By addressing this point in the recast electricity directive, the European Commission has set the first steps, which now must be implemented using secondary legislation such as the Network Codes.

Recommendation 5: Establishing energy storage as a separate asset class

EASE calls upon EU policy makers to go further than the proposed regulation and directive by establishing energy storage as a separate asset class, as called for by the European Parliament. Energy storage should be recognised as the fourth element of the energy system (alongside generation, transport (transmission/distribution), and consumption). This would prevent energy storage from being classified as either generation or consumption – or as both. Such a fourth element status would eliminate any ambiguity that results from the historical market design stemming from a centralised energy system where everything fit into one of the three categories. It would also allow for a clear framework specific to energy storage, clarifying amongst others the unwarranted double charging (including levies and taxes) on energy storage devices and the ownership of energy storage facilities.

7.2 Conclusions

The above set of barriers is illustrative and not exhaustive; there are numerous other entry barriers which could be enumerated here. The rapid development and deployment of energy storage technologies, as well as their integration into the grid, could be supported with broader regulatory reform and the elimination of these

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barriers. When discussing R&I efforts, it is important to underline that a supportive regulatory framework for storage is vitally important to the market roll-out of innovative storage technologies.
8. Recommendations and Proposed Timeline for Activities

The transition to a sustainable, low-carbon energy system is already well underway in Europe. Energy storage is poised to play a vital role in supporting that transition, although the size of its contribution depends on further technological developments and cost reductions for storage. An effective and coordinated R&D effort in Europe can support the burgeoning storage industry, particularly if coupled with a promising regulatory environment and increased private investment for commercialisation.

Given the large range of storage technologies, which are at varying TRLs and suitable to many different applications, prioritisation of R&D efforts in the energy storage domain is extraordinarily difficult. The below recommendations take into account the most important cross-cutting priorities mentioned for all energy storage technologies; the most promising business cases and applications for storage, both today and in the near future; and the most pressing issues in the energy transition that could be addressed through storage (e.g. integrating variable RES, decarbonising heating and cooling and transport).

8.1 Identification of Energy Storage R&D Priorities

In chapter 6, we identified research priorities specific to each energy storage technology. One common theme is the need to reduce the cost of storage: this is considered one of the top priorities to address for each family of storage technologies. This can be done through a focus on materials research, manufacturing processes, and efforts to improve integration with other system components. Another overarching theme is the need to research energy storage business cases and to clarify the technical requirements and economics of aggregating different energy storage services.

To identify R&D priorities for the short, medium, and long-term, it is helpful to consider the promising business cases and applications for energy storage in those timescales. In the coming years, the most promising energy storage applications, based on commercial business cases, are in the short-term electricity balancing market. Ancillary services, including new ones being proposed by the UK and Ireland, are already offered by energy storage devices.

In a medium-term perspective (5–10 years), not only ancillary services but also energy arbitrage based on stored energy could be a valuable application. Investment deferral, both at the DSO and TSO levels, could be a further promising application, but is dependent on solving the ownership question. Self-consumption and storage of renewable electricity could also become more wide-spread.
20 years from now, energy storage will likely play an important role in linking the electricity system closely to its neighbouring sectors in the energy system, thereby decarbonising them. Private as well as industrial heat demand are obvious candidates for future supply from the electricity system and the transport sector will undoubtedly - although perhaps at a slower rate - be shifted to supply by energy based on sustainable electricity. Energy storage applications able to support the decarbonisation of heating and cooling and transport will become increasingly valuable.

8.2 Recommendations and Timeline

Below, we summarise the R&D priorities we consider most pressing for the industry as a whole. We situate these along a rough timeline, based on an assessment of the most pressing needs and of which efforts are likely to yield the most promising returns for the energy system.

We recommend the following timeline for energy storage RD&D projects in Europe:

**Within the next 2 years:**

- Set up European demonstration and pilot programmes focusing on grid integration of relatively mature energy storage technologies. These programmes will be necessary to support the deployment of the technologies needed within a short timeframe to integrate growing shares of RES. Pilot programmes would be particularly valuable for chemical storage, grid-scale battery storage, new advancements of PHS technology in terms of flexibility or development potential, and intermediate heat storage for adiabatic CAES. Such demonstration projects will, within 5–10 years, yield valuable experience for design and manufacturing processes for cost-effective large-scale industrial production. Demonstration projects will also allow for collecting information on grid integration of energy storage devices.

- Support materials and equipment research to allow improving and understanding performance of crucial components and parts in energy storage facilities. Such efforts will have impact on both economy, performance and flexibility of storage technologies. In particular, research on materials for energy storage technologies could have an important effect on reducing storage system cost. This would include low cost materials for hydrogen storage as well as thermal storage, novel materials for completely new electrochemical systems (e.g., metal–air, liquid batteries, Mg–based batteries, organic batteries,...), and nitride and sulphide materials for capacitors.
- Designate energy storage as an Important Project of Common European Interest (IPCEI). IPCEIs aim to encourage Member States to direct public spending to large projects that make a clear contribution to economic growth, jobs, and competitiveness of European industries. IPCEIs can receive several forms of support (e.g., repayable advances, loans, guarantees or grants from Member States), aid for the first industrial deployment of an R&D, and are exempt from state aid measures. Designating energy storage as an IPCEI could help build a strong European manufacturing base for key energy storage technologies that could allow Europe to be globally competitive.

- Carry out intensive research efforts at the grid integration level in order to decrease storage system costs and to facilitate the aggregation of different applications. This includes software development to improve modelling and control the use of energy storage technologies.

- Identify possible market models/use cases able to guarantee the economic feasibility of energy storage devices and assess how markets could be improved in order to allow the full deployment of energy storage. This should be done in a joint effort between the EU Member States to secure the highest degree of alignment.

- Develop a strategic energy storage plan for Europe, detailing how to conduct strategic development and planning of energy storage potential in Europe, alongside strategic plans for infrastructure development, supply–side development and demand–response options in the most cost–effective way. Plans should include a regional/local assessment of specific energy storage potential and needs given specific local circumstances regarding supply, demand, and energy infrastructure.

- Initiate a long–term, coordinated research effort among leading private companies and research laboratories across Europe with common expertise related to energy storage technologies.

- Sustain laboratory scale (or equivalent) development and assessment of new, still unproven, energy storage ideas and concepts to allow subsequent qualified judgment of their potential and viability for further support and applicability. Such efforts may be high–risk, but they could allow for new advancements and novel ideas not even perceived today.

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Within the next 2–5 years:

- Analyse degradation processes related to diverse duty cycles (including modelling) to allow for predictive maintenance, increased reliability, and improved designs and manufacturing processes.
- Study system integration, focusing on how gas, electricity, heat, and other infrastructures (e.g. refuelling infrastructure) can be combined and complemented with storage of gas, electricity, heat, and/or fuels.
- Systematically demonstrate the ways in which energy storage can provide energy services and monetise the added value to the energy system. Demonstrating the effective use of energy storage devices not only from a technical but also from an economic point of view would greatly facilitate their deployment. Such an assessment could consider energy storage installations at each location in the grid in order to identify at which point of the grid energy storage could provide different applications in the most cost–effective way.
- Investigate new designs for energy storage and hybrid technologies and analyse requirements for optimal integration.
- Continue basic materials research initiated in the first 2–year period.

Within the next 5–10 years:

- Support new large–scale demonstration projects based on the experience gained from the first phase projects and including results obtained from materials research and modelling efforts.
- Continue basic materials research and evaluation of new ideas and continuously check R&D status against application requirements.
- Support communication and interaction of different storage assets in the grid for supplying ancillary services and load shifting.
- Conduct research on energy storage in relation to the expected expansion of EVs, including vehicle–to–grid services and the use of second–hand EV batteries for stationary applications.

The above recommendations attempt to consolidate the many R&D priorities and considerations enumerated for each energy storage technology. They are based on assumptions on the evolution of the electricity system and energy storage technologies in Europe. However, technological breakthroughs in storage technologies and/or other flexibility options may completely change the basis for the present recommendations.
Moreover, it is important to note that the recommendations given in the present Roadmap should not preclude supplementary R&D interest and resources in other technologies that are not presently believed to hold a commercial potential in the 10–20 year period.
LIST OF FIGURES

Figure 1: Worldwide installed energy storage capacity ............................................................. 17
Figure 2: Overview of energy storage applications. Source: EASE ............................................ 18
Figure 3: Overview of different energy storage technologies .................................................. 24
Figure 4: Technical maturity of chemical storage components ............................................. 34
Figure 5: Battery market growth (MWh) 1990–2015, Avicenne Energy, 2016 ......................... 42
Figure 6: compilation by EMIRI, EUROBAT, EASE, and Technofi, 2016 .............................. 43
Figure 7: Cost estimates and future projections for electric vehicle battery packs, measured in US $ per kilowatt hour of capacity. Each mark on the chart represents a documented estimate reviewed by the study. Source: Nykvist et al. (2015) ........................................ 44
Figure 8: Energy storage applications segmented by discharge time .................................. 45
Figure 9: Tentative Roadmap for supercapacitors with vision to 2030 (prepared by CNR–ITAE from) .................................................................................................................................................. 55
Figure 10 – SMES buffering of mechanical, chemical, electrochemical or cryogenic Energy Storage Systems ................................................................................................................................. 57
Figure 11 – LIQHYSMES Storage Unit based on hydrogen for long term energy storage and SMES for short term storage ......................................................................................................................... 57
Figure 12: LAES mode of operation .......................................................................................... 73
Figure 13: Principle of a Pumped Hydro Storage plant ............................................................ 79
Figure 1 – Timeframes for modern advanced PHS unit regulation ........................................ 81
Figure 15: Crescent Dunes molten salt storage tank ................................................................. 87
Figure 16: aerial view of Crescent Dunes molten salt storage (Source: COBRA) .................... 88
Figure 17: Latent storage system with 700 kW power, 1h storage capacity, Source: DLR .... 95
Figure 18: Test stand for thermal upgrade of waste heat at T>140°C. Source: DLR ............ 100

LIST OF TABLES

Table 1: SET Plan targets Alkaline Technology ....................................................................... 35
Table 2: SET Plan targets PEM Technology ............................................................................. 35
Table 3: SET Plan targets Solid Oxide Technology ................................................................. 36
Table 4: SET Plan targets Plasmology CO2 ............................................................................ 36
Table 5: SET Plan targets Hydrogen Storage Technologies .................................................... 37
Table 6: Status of development of major electrochemical storage systems for grid applications ........................................................................................................................................... 41
Table 7: Comparison among different electrochemical storage systems for the different discharge times corresponding to the different energy storage applications.............. 45
Table 8: SET Plan targets for electrochemical storage............................................... 46
Table 9: SET Plan targets for supercapacitor* technologies towards 2030 and beyond .... 53
Table 10: Economic SET Plan targets for supercapacitor technology towards 2030........... 53
Table 11 – Targets for SMES materials towards 2030 and beyond................................. 59
Table 12: Targets for SMES materials, technology and systems towards 2030 and beyond. 60
Table 13 Application potentials of CAES related technology........................................... 65
Table 14. The theoretical values of the maximum energy efficiency................................. 66
Table 15: SET–Plan targets .................................................................................................. 70
Table 16: SET–Plan targets .................................................................................................. 76
Table 17 – PHS features (VS = variable-speed, TS = Ternary Set)................................. 80
Table 18 – SET Plan targets for hydro energy storage technologies towards 2030 and beyond ............................................................................................................... 82
Table 19 – Estimated R&D needs for hydro energy storage technologies ....................... 85
Table 20: Applicability of thermal storage technologies for different applications .......... 87
Table 21: Characteristics of low/high temperature sensible energy storage technologies... 88
Table 22: Characteristics of LHS technologies ................................................................. 95
Table 23: Characteristics of TCS technologies ................................................................. 99