Joint EASE/EERA recommendations for a

EUROPEAN ENERGY STORAGE TECHNOLOGY DEVELOPMENT ROADMAP

2017 UPDATE

EASE

EERA
European Energy Research Alliance
Energy Storage

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 the EU's ambitious clean energy and climate policies. EASE members come from all sectors of the energy storage value chain and 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.

EERA, the European Energy Research Alliance, is an alliance of leading organisations in the field of energy research. EERA aims to strengthen, expand, and optimise EU energy research capabilities through the sharing of world-class national facilities in Europe and the joint realisation of pan-European research programmes (EERA Joint Programmes). The EERA Joint programme on Energy Storage is the first pan-European programme to bring together all major fields of energy storage research. The primary focus of EERA is to accelerate the development of energy technologies to the point where they can be embedded in industry-driven research. In order to achieve this goal, EERA streamlines and coordinates national and European energy R&D programmes.

For further information, please visit www.eera-set.eu and www.eera-es.eu

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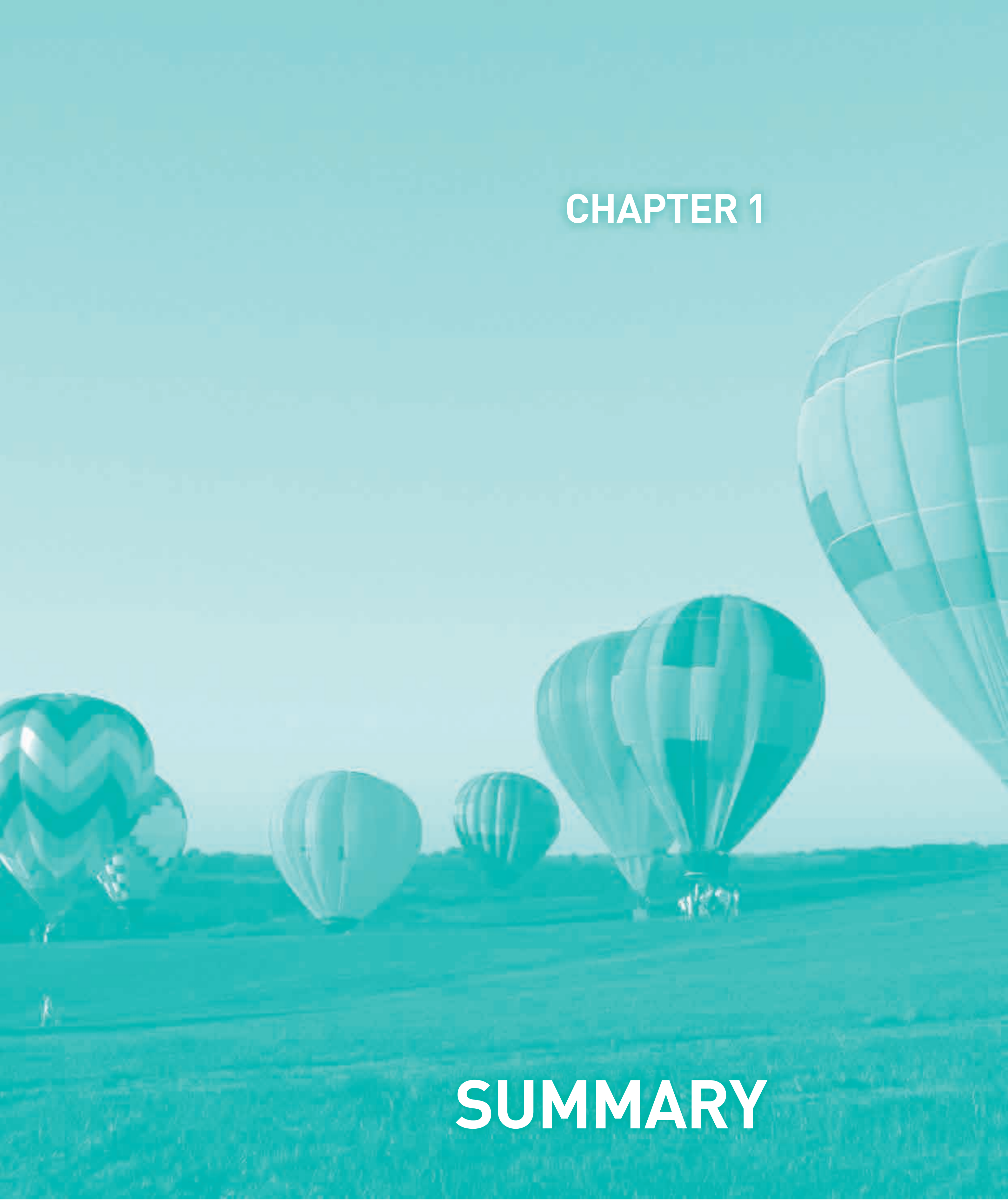


CHAPTER 1

SUMMARY

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 evolution and advancements 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). 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 focus on stationary applications, and identifies the most pressing research, development and demonstration (RD&D) needs in the coming decades. Where applicable, energy storage for electro mobility is also considered in the technology sections. On this basis, the roadmap provides recommendations for research and development (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.

More information about the methodology used to elaborate this roadmap is contained in Chapter 2. Chapter 3 lists the mission and objectives. 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 and, explains the key applications for the electrical system and for sector interfaces. This Chapter also 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 their 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. An 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. Therefore, we make the following recommendations:

1 EASE/EERA European Energy Storage Technology Development Roadmap, 2013. http://ease-storage.eu/wp-content/uploads/2015/10/EASE-EERA-recommendations-Roadmap-LR.pdf

1. Remove regulatory barriers to enable innovative, first-of-a-kind demonstration projects to study the technical feasibility and market applications of energy storage systems.

2. Establish a definition of energy storage in the EU regulatory framework.

3. 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.

4. Eliminate unwarranted/double charging in a coordinated approach at European level. Whether and to what extent storage should finally contribute to grid costs merits a dedicated debate at European level. Energy storage usually alleviates the grid and is a complement to grid development. It follows that storage should be exempted from grid charges, or only have a relatively small contribution.

5. Ensure that the procurement of all energy and ancillary services is market-based, subject to a cost-benefit analysis (CBA).

6. Establish energy storage as a separate asset class, next to generation, transmission/distribution, and consumption. This would ensure that the regulatory framework recognises the unique aspects of energy storage vis-à-vis the other assets.

In Chapter 8, we summarise the R&D priorities we consider most pressing for the industry as a whole. One cross-cutting priority is the need for cost reductions: this is considered the most important goal for each family of storage technologies. 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. Lastly, we believe that the promising area of hybrid energy storage systems, combining two or more technologies, merits increased attention in RD&D programmes.

In addition to these overarching priorities, we identify a number of RD&D priorities based on the most immediate needs and on the likelihood of yielding promising returns. We situated these needs along a rough timeline:

Within the next 2 years:

- Set up European demonstration and pilot programmes focusing on grid integration of relatively mature energy storage technologies.

- Systematically demonstrate the ways in which energy storage can provide energy services and monetise the added value to the energy system.

- Support materials and equipment research to allow improving and understanding performance of crucial components and parts in energy storage facilities.

- Designate energy storage as an Important Project of Common European Interest (IPCEI)[2].

2 See European Commission: State Aid: Commission Adopts New Rules to Support Important Projects of Common European Interest, 2014. http://europa.eu/rapid/press-release_IP-14-673_en.htm

- 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.

- Initiate a long-term, coordinated research effort among leading private companies and research laboratories with common expertise related to energy storage technologies to identify and promote ways to successfully scale up technologies within the EU.

- Support laboratory scale development and assessment of new, still unproven, energy storage ideas and concepts to judge their potential and viability for further support and applicability.

Within the next 2-5 years:

- 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.

- Analyse degradation processes related to diverse duty cycles 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.

- Conduct research on energy storage in relation to the expected expansion of electric vehicles (EV), including vehicle-to-grid services and the use of second-hand EV batteries for stationary applications. Assess the relative merits of services from stationary vs mobile (aggregated EV) storage facilities, and identify opportunities for mutual learning.

- 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.

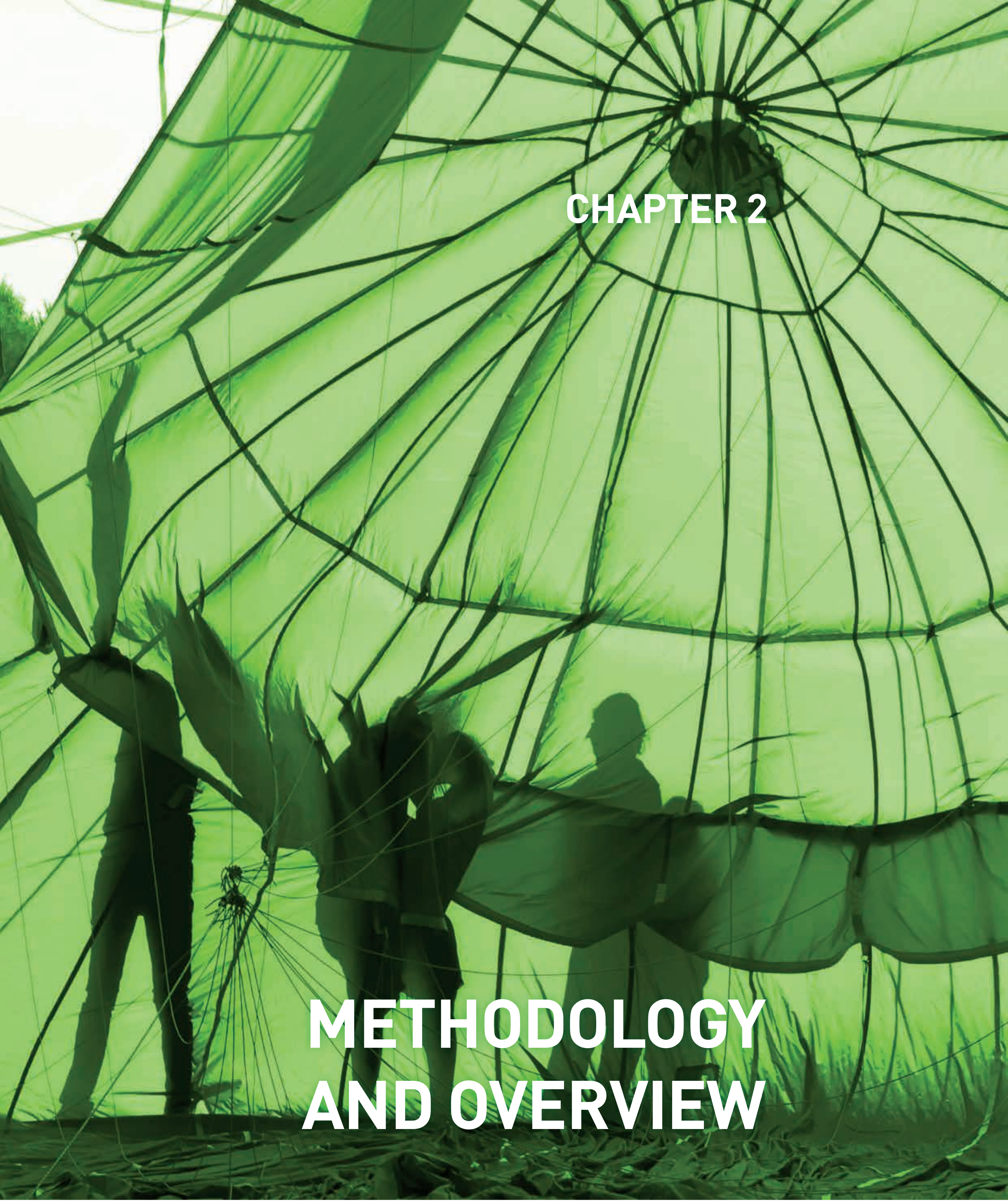
Within the next 5-10 years:

- 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 RD&D status against application requirements.

- Support communication and interaction of different storage assets in the grid for system services and load shifting.

- We believe that pursuing a coordinated RD&D policy for energy storage, taking into account the above recommendations, could help Europe become not only a world leader in renewables, but also a global leader in deploying cost-effective and innovative energy storage technologies.



CHAPTER 2

METHODOLOGY AND OVERVIEW

2 METHODOLOGY AND OVERVIEW

The first EASE/EERA roadmap was published 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.

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 fossil fuels in short time intervals).

Given this clear demand for energy storage capacity and services to respond to the challenges of a RES-dominated energy system, there is 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 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 sub programme 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 ensuring that the roadmap includes a wide range of expertise and reflects the viewpoints of the diverse and vibrant European energy storage community. Following the principles of transparency and openness, we invited a group of relevant stakeholders to contribute to this joint roadmap. The stakeholders had different possibilities to provide feedback along the process: by sending written comments on the first draft and

3 Yasmin Ali: Cryogenic Storage Offers Hope for Renewable Energy, BBC News, 2016. http://www.bbc.com/news/science-environment-37902773

4 Schwungrad Energie: Schwungrad Energie's Official Opening of its Hybrid Flywheel-Battery Pilot, 2015.http://schwungrad-energie.com/schwungrad-energies-official-opening-hybrid-flywheel-battery-pilot/

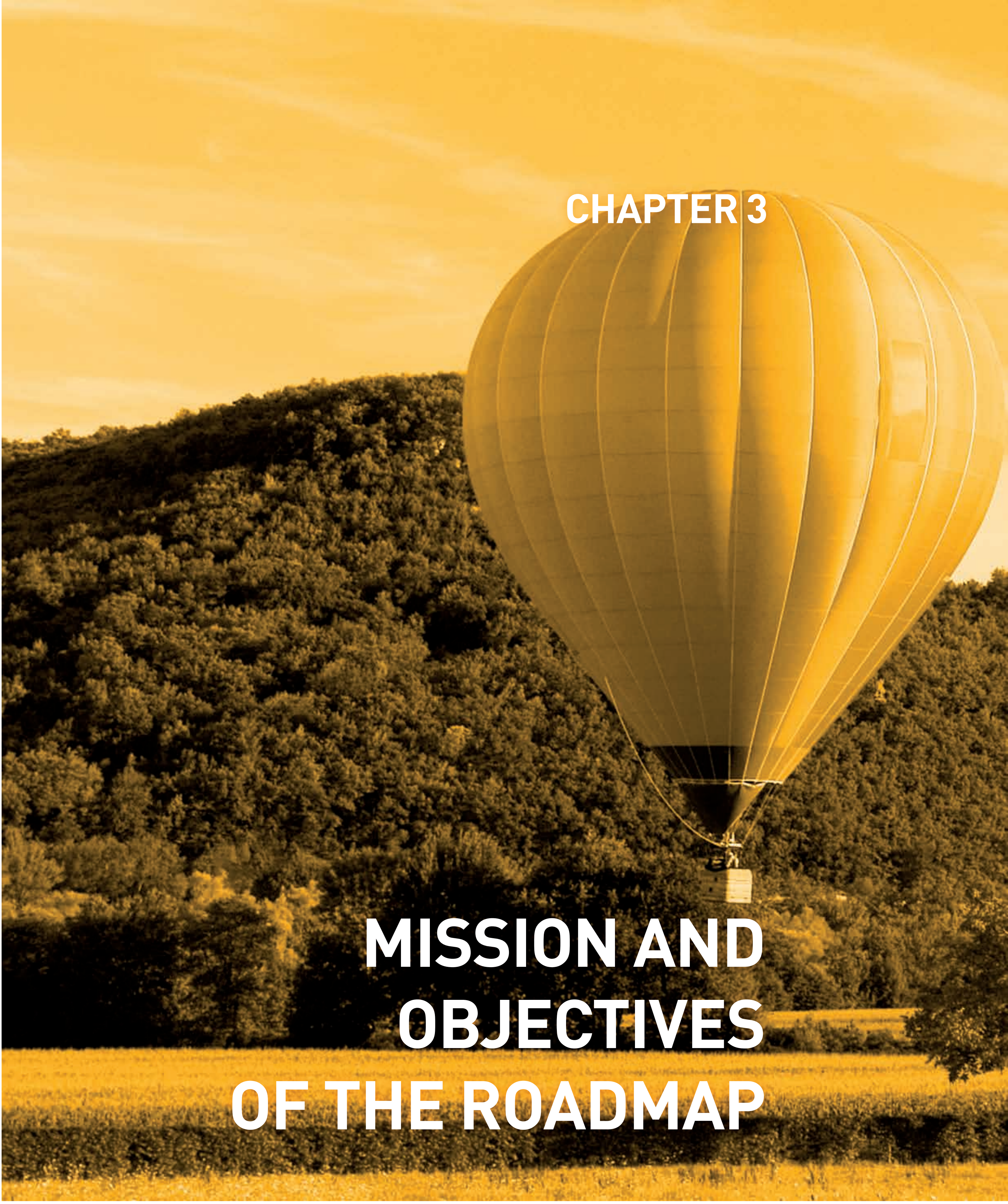
5 Prices for Li-ion batteries have declined by more than 50% since 2010, according to Moody's Investor Service: Declining Battery Prices Could Lead to Commercial and Industrial Customer Adoption In 3-5 Years, 2015. https://www.moodys.com/research/Moodys-Declining-battery-prices-could-lead-to-commercial-and-industrial-PR_335274

by providing additional comments during a stakeholder's workshop organised by EASE and EERA in March 2017.

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 Technologies[6]. However, since that roadmap stems from 2011, the targets have been updated by EASE-EERA contributors to reflect recent technological developments. Due to the difficulty of gathering comparable information on all energy storage technologies, some fields in the tables were left blank. Even so, the tables serve as a useful starting point to identify the gaps between current performance and the future targets.

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

6 Commission Staff Working Paper: Materials Roadmap Enabling Low Carbon Energy Technologies, 2011. http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view



CHAPTER 3

MISSION AND OBJECTIVES OF THE ROADMAP

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 actions on energy storage for the Horizon 2020 and post-Horizon 2020 research frameworks, in line with the European Energy Union goals. These actions will facilitate the integration of RES 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 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.

CHAPTER 4

EUROPEAN AND GLOBAL POLICY AS A DRIVER FOR ENERGY STORAGE DEMAND

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, 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 in July 2015 a legislative proposal to review the EU Emission Trading Scheme for the period 2021-2030. This was followed by the "Clean Energy for All Europeans" package in November 2016[9].

7 The package set three key targets: 20% cut in greenhouse gas emissions (from 1990 levels), 20% of EU energy from renewables and 20% improvement in energy efficiency. European Commission: 2020 Climate & Energy Package, 2007.http://ec.europa.eu/clima/policies/strategies/2020/index_en.htm

8 United Nations Framework Convention on Climate Change: Paris Agreement, 2015. http://unfccc.int/paris_agreement/items/9485.php

9 European Commission: Commission Proposes New Rules for Consumer Centred Clean Energy Transition, 2016. https://ec.europa.eu/energy/en/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition

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; and the Directive on Energy Efficiency. The aspects of the package specifically touching on energy storage, as well as other barriers affecting the energy storage business case, were addressed by the Commission in a Staff Working Document issued in February 2017[10].

Energy research and innovation (R&I) 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"[11]. 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[12]. 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[13]. 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.

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[14].

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

10 European Commission: Commission Staff Working Document Energy Storage – the Role of Electricity, 2017. https://ec.europa.eu/energy/sites/ener/files/documents/swd2017_61_document_travail_service_part1_v6.pdf

11 European Commission: A Framework Strategy for a Resilient Energy Union with a Forward-Looking Climate Change Policy, 2015. http://eur-lex.europa.eu/legal-content/en/TXT/?uri=COM%3A2015%3A80%3AFIN

12 European Commission: Communication on Accelerating Clean Energy Innovation, 2016. http://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v6_0.pdf

13 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.

14 International Energy Agency: Energy Technology Perspectives, 2014. www.iea.org/publications/freepublications/publication/EnergyTechnologyPerspectives_ES.pdf European Commission: Energy Roadmap 2050, 2011.

between €1.5 and €2.2 trillion between 2011 and 2050[15], 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[16]. 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 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"[17]. 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[18] and the European Parliament[19] recognise the importance of energy storage, the regulatory framework has not yet evolved to support its cost-efficient deployment. 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 proposal for a revised Electricity Directive[20] issued by the Commission in November 2016. Requirements in the Network Codes, which in some cases can be onerous for energy storage devices, 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.

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15 European Commission: Energy Roadmap 2050, 2011. http://eur-lex.europa.eu/legal-content/en/ALL/?uri=CELEX%3A52011DC0885

16 International Energy Agency: Technology Roadmap Energy Storage, 2014. https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergystorage.pdf

17 European Commission: Energy Storage, 2016. https://ec.europa.eu/energy/en/topics/technology-and-innovation/energy-storage

18 European Commission: Energy Storage – Proposed Policy Principles and Definition, 2016. https://ec.europa.eu/energy/sites/ener/files/documents/Proposed%20definition%20and%20principles%20for%20energy%20storage.pdf

19 See European Parliament: Energy Storage: Which Market Designs and Regulatory Incentives are Needed?, 2015. www.europarl.europa.eu/RegData/etudes/STUD/.../IPOL_STU(2015)563469_EN.pdf and European Parliament: Report Towards a New Energy Market Design, 2015/2322 (INI), 2015.

20 European Commission: Directive on Common Rules for the Internal Market In Electricity, 2016. http://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v7_864.pdf

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[21] - 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[22]. 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 strengthen efforts to re-industrialise Europe, contributing to long-term growth for European citizens while supporting the EU's ambition to make Europe the world number one in renewables.

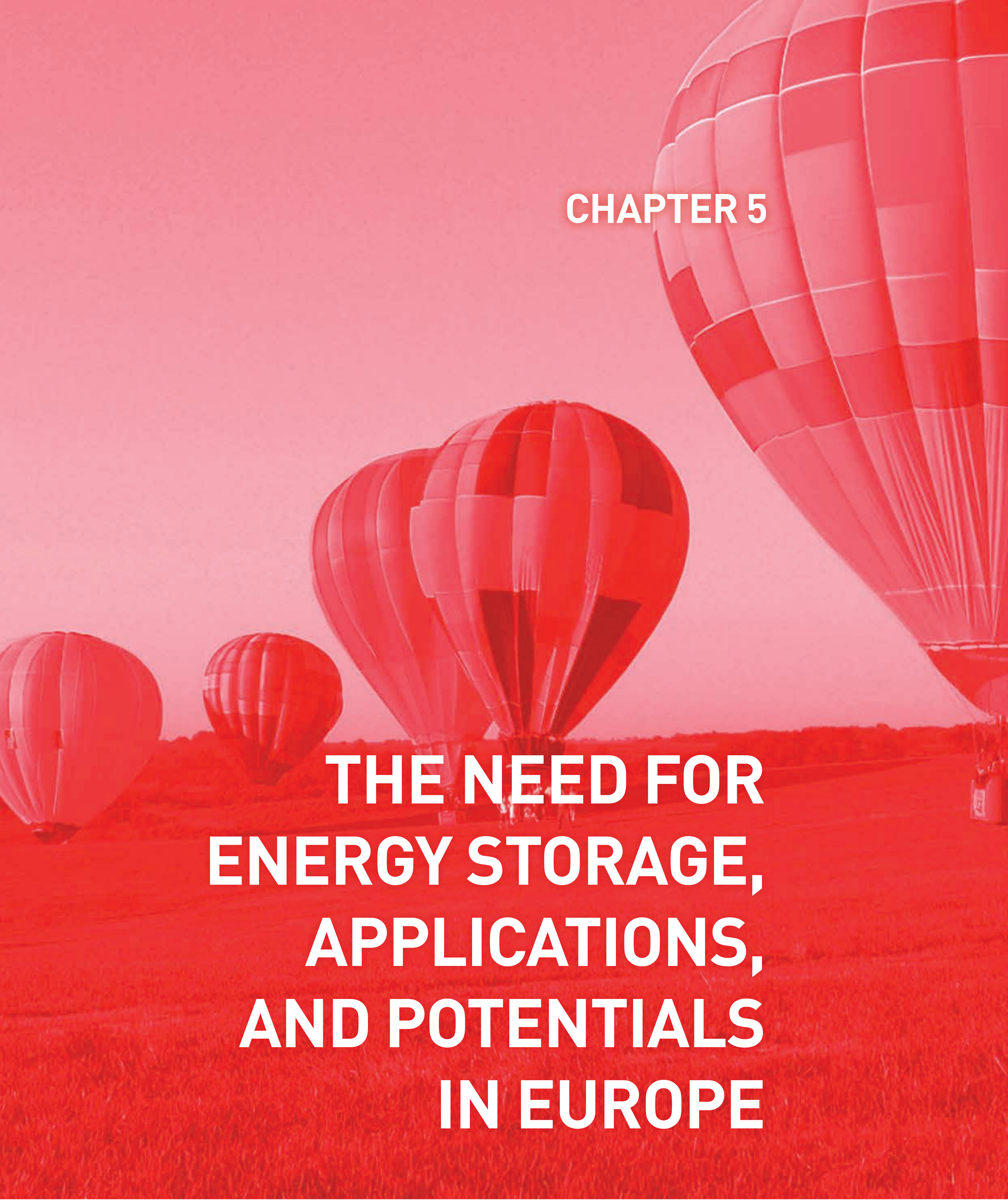
However, achieving this industrial growth will require support from policy makers, on par with efforts being made by governments of other countries. For some energy storage technologies, the European industry has a strong leadership position. For others, European companies are competing fiercely for 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 projects 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.

21 European Commission: Imports and Secure Supplies: Diverse, Affordable, and Reliable Energy from Abroad, 2016. https://ec.europa.eu/energy/en/topics/imports-and-secure-supplies

22 Bloomberg New Energy Finance: New Energy Outlook 2016, 2016. https://www.bloomberg.com/company/new-energy-outlook/



CHAPTER 5

THE NEED FOR ENERGY STORAGE, APPLICATIONS, AND POTENTIALS IN EUROPE

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, the electrification of the heating and cooling sector, 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 emissions, decreasing import dependency on fossil fuels, and improving the return on renewable energy generation investments.

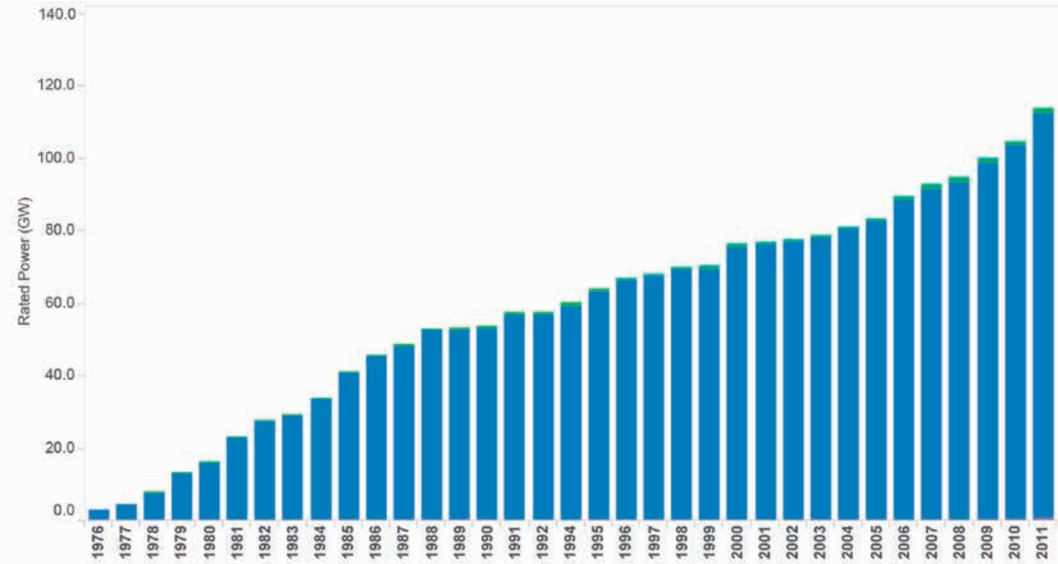
There is a need to further increase energy efficiency and to reduce CO_2 emissions. Energy storage will, for example, contribute to a higher efficiency for energy-intensive industrial processes and more flexibility for conventional power plants.

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 links between different energy carriers. This is the so-called Power-to-X (P2X) scheme that couples the electricity sector to the gas and oil sectors, providing both effective long-term large-scale energy storage by existing infrastructure and a solution to decarbonise road, sea, and air transport.

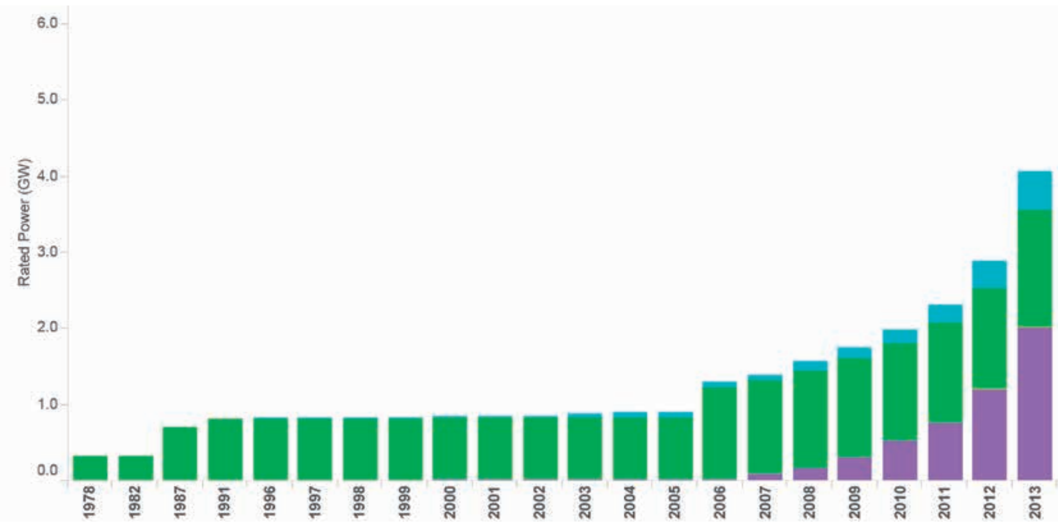
In 2015, installed large-scale energy storage capacity world-wide was estimated at 150 GW with approximately 96% of this capacity consisting of pumped hydro storage (PHS)[23]. More than 70% of new installations completed in 2014 are still PHS. The development of worldwide installed energy storage capacity in recent years is shown in figure 1. It shows that thermal energy storage, large-scale batteries, flywheels, and compressed air energy storage (CAES) are the main components of the non-PHS energy storage capacity.

23 IEA: Tracking Clean Energy Progress, 2016. https://www.iea.org/publications/freepublications/publication/tracking-clean-energy-progress-2016.html

Global Energy Storage Project Installations



Global Energy Storage Project Installations – excluding PHS



- Electrochemical Storage
- Electromechanical Storage
- Hydrogen Storage
- Thermal Storage
- Pumped Hydro Storage

Figure 1: Globally Installed Energy Storage Capacity, 1978 – 2016[24].

24 EASE adaptation of DOE Global Energy Storage Database, August 2017. https://www.energystorageexchange.org/

Several forecasts[25], [26], [27] 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[28], which would result in 2 GW of new installations by 2021.

5.2 Energy Storage Applications – Electricity Sector

The different energy storage applications can be segmented according to the discharge time and response time, as shown in figure 2.

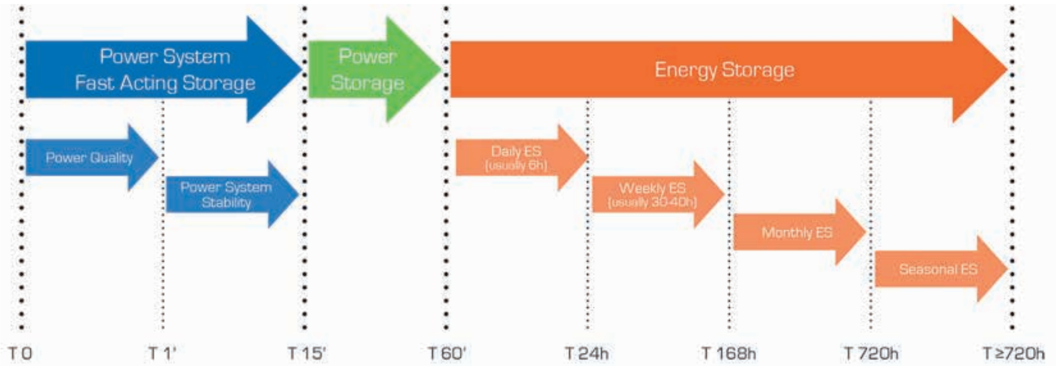


Figure 2: Energy storage applications segmented by discharge time[29].

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

25 Bloomberg New Energy Finance: New Energy Outlook 2016, 2016. https://www.bloomberg.com/company/new-energy-outlook/

26 International Energy Agency: World Energy Outlook 2016, 2016. www.iea.org

27 Navigant Research: Market Data: Commercial & Industrial Energy Storage, Q1 2016. https://www.navigantresearch.com/research/market-data-commercial-industrial-energy-storage

28 GTM Research/ESA: U.S. Energy Storage Monitor: Q2 2016, 2016. https://www.greentechmedia.com/research/subscription/u.s.-energy-storage-monitor

29 EASE: Annual Report, 2014. http://ease-storage.eu/wp-content/uploads/2015/10/EASE-Activity-Report-2014_LR.pdf

Generation/Bulk Services	Ancillary Services	Transmission Infrastructure Services	Distribution Infrastructure Services	Customer Energy Management Services
Arbitrage	Primary frequency control	Transmission investment deferral	Capacity support	End-user peak shaving
Electric supply capacity	Secondary frequency control	Angular stability	Contingency grid support	Time-of-use energy cost management
Support to conventional generation	Tertiary frequency control	Transmission support	Distribution investment deferral	Particular requirements in power quality
Ancillary services RES support	Frequency stability of the system		Distribution power quality	Maximising self-production & self-consumption of electricity
Capacity firming	Black start		Dynamic, local voltage control	Demand charge management
Curtailment minimisation	Voltage support		Intentional islanding	Continuity of energy supply
Limitation of disturbances	New ancillary services		Limitation of disturbances	Limitation of upstream disturbances
			Reactive power compensation	Reactive power compensation
				EV integration

Figure 3: Overview of energy storage applications in the electricity sector. 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:
  - o 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.
  - o 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.
  - o Hedging imbalance: charges due to deviations of final physical notifications.

- **Ancillary services RES support** is the use of energy storage to help variable 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 variability 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. This can either be delivered to the electricity grid when needed or converted it into another energy vector (gas, fuel or heat) to be delivered to the relevant grid or used in industrial processes.

- **Limitation of 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.
    - Reduce minimum load violations.

System Needs/Ancillary Services

- **Primary frequency control (FRR/FCR)** 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.

- **Secondary frequency control (FRRa)** 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 (FRRm)** 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** is a service that aims to maintain the frequency stability by helping avoid load shedding on islands thanks 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 or a substation 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 transmission system operators (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 synthetic inertia, ramping margin, fast frequency response, dynamic reactive response, etc.

Transmission

- **Transmission investment deferral** is the use of energy storage to solve transmission congestion issues, thereby deferring transmission infrastructure upgrades.

- **Angular stability** refers to the use of energy storage to charge and discharge high levels of energy in short periods when an accident occurs. This may contribute to reducing the load-angle variations, thus improving the angular stability of the system.

- **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, e.g. 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, thereby solving distribution congestions.

- **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 an intentional 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 TSOs, with rules set according to Network Codes, which require 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 the grid's reactive power balance.

In this context energy storage may also include "virtual" storage systems, when for example industrial electricity demand is being shifted by changing the operational time profile of an industrial process.

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 price 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 disturbances** is the use of energy storage for the limitation of disturbances in the network.

- **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 – Heat Sector

Within the heat sector, space heating and hot water production at low temperatures have to be distinguished from (industrial) process heat with a wide temperature range. Energy storage has already found widespread commercial utilisation in various low temperature applications and will play an increasingly important role in both areas.

Space Heating and Hot Water Production

- Decentralised water storage vessels are used to offset daily fluctuations and increase the solar share of solar thermal domestic heating systems.

- Decentralised seasonal storages with high storage density being charged either from solar thermal and/or PV could be used to optimise self-supply of heating needs in winter from renewable energy.

- District heating systems are often equipped with large water tanks at temperatures up to 120°C to:
    - Decouple electricity and heat generation to better meet demand and optimise revenues,
    - Overcome short periods of plant shutdown,
    - Enable Power-to-Heat operation in times of low electricity prices (see following section on Energy Sector Interfaces).

- District heating systems, if driven by solar thermal, photovoltaic, or geothermal energy, are equipped with seasonal underground storages to shift energy from the summer into the winter, when it is needed. Energy storage can optimise the efficiency of production, shift the production from partial load (typically lower efficiency then base load) to base load production (typically higher efficiency then partial load operation), and shift the production (in case of cogeneration) from low electric demand to high electric demand. These applications could lead to an improvement of the energy system, both in terms of energy efficiency issues and of environmental issues.

(Industrial) Process Heat

- High-temperature thermal energy storages are used to increase the efficiency of power plants or industrial processes through recovery of fluctuating waste heat streams for re-integration or continuous electricity production. This can lead to decreases in CO_2 emissions as well as financial and energy savings[30].

30 Laia Miró, Jaume Gasia, Luisa F. Cabeza: Thermal Energy Storage (TES) for Industrial Waste Heat (IWH) Recovery: A Review. Applied Energy Volume 179, pp. 284–30, 2016.

- Thermal energy storage systems can also be used to guarantee the continuous supply of process heat generated from fluctuating renewable electricity. This will become increasingly relevant when higher shares of renewables are in the energy system.

- Industrial cogeneration plants can be operated more flexibly, if thermal energy storage is integrated, thus optimising revenues and better meeting demands.

5.4 Energy Storage Applications – Energy Sector Interfaces

In addition to the specific benefits of storage applications in the electricity and heat sector outlined above, energy storage is able to provide additional services to the energy system by integrating the electricity, heating & cooling, gas, and transport sectors. Such technologies can help provide competitive flexibility to the EU electricity system and can transfer the share of renewables originally generated in the electricity sector to other sectors.
These applications include:

- Power-to-Chemicals, meaning synthesis of intermediates and higher-value chemical products from renewable electricity and, if necessary, any carbon sources. The products can be considered long-term (weekly, monthly or seasonal) energy storage of renewable electricity. In most cases electrochemical conversion via electrolysis is included as a first step, followed by further synthesis processes. Possible routes include:
    - Power-to-Hydrogen for application as transportation fuel, as combustion fuel for heating or as chemical raw materials,
    - Power-to-Gas (synthetic natural gas) that can be easily integrated into the existing infrastructure to replace fossil natural gas,
    - Power-to-Liquid which includes longer-chain hydrocarbons that will be used in the transport sector, such as in air, maritime or heavy-load traffic, where fuels with high energy content will be needed in the long run.

- Power-to-Heat deals with the conversion of electricity into thermal energy. Various technologies could be applied here at different temperature levels, namely:
    - Night storage heating for domestic applications has a long tradition of being charged at times of low electricity prices and providing decentralised renewable heat,
    - Electrode boilers and/or heat pumps in combination with large thermal energy storages at heating plants already supply district heating networks with renewable heat on demand,
    - In the long run, thermal energy storages heated with renewable electricity can provide constant process heat at the desired temperature level with cost-efficient storage technologies (see the previous Chapter).

The utilisation of such technologies highly depends on the price of electricity as well as the cost for the conversion process. In the case of Power-to-Chemicals, this cost is dominated mainly by the investment cost of electrolysis. Power-to-Heat technologies, meanwhile, can currently be realised at a lower cost.

Lastly, there is also a need to further integrate the energy and transport sectors as electric and fuel cell/hybrid vehicles become more widespread. Energy storage technologies can support charging and refuelling infrastructure, while these vehicles could provide valuable flexibility services to the grid.

5.5 Introduction to Energy Storage Technologies

Energy storage technologies are commonly classified according to storage principle, or family, as seen in figure 4. 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.

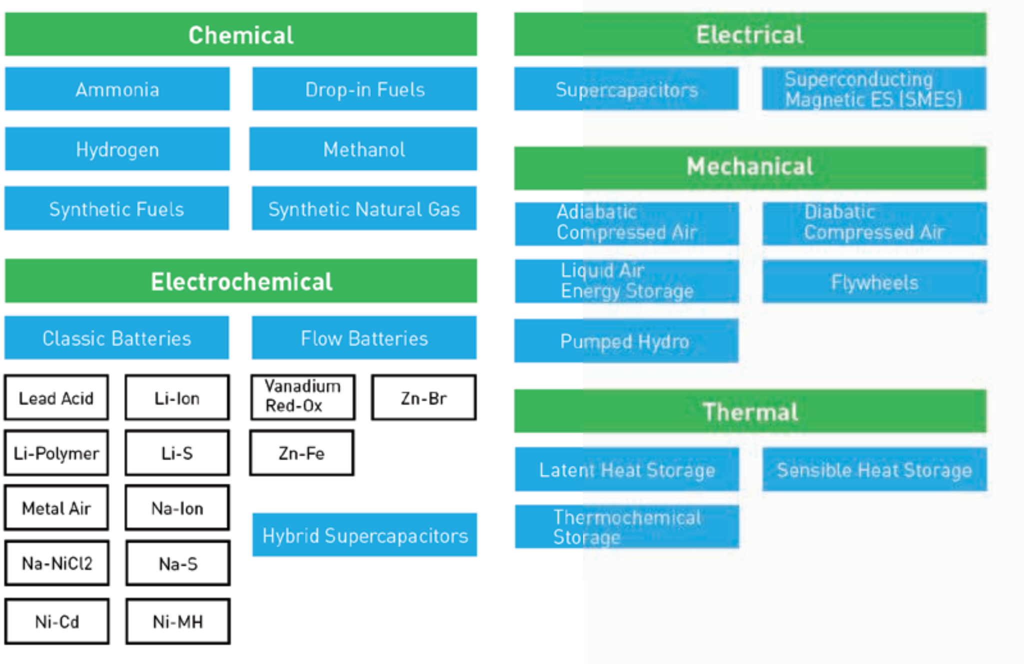


Figure 4: Overview of different energy storage technologies. Source: EASE.

- 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 and vice-versa in electrochemical reactions. There are many options that differ in electrode and electrolyte materials and as a result in their major parameters. They can be split into two broad 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. Energy can be stored in the sensible heat of materials undergoing a change in temperature. Latent heat storage takes advantage of the energy absorbed or released during a phase change and thermo-chemical energy storage utilises the heat evolution of a physical process or a chemical reaction. In general, thermal storage is quite cost-effective compared to other storage options.

A detailed explanation of each kind of energy storage is given in Chapter 6. While each technology can be deployed on its own, there is also the possibility to combine different energy storage technologies with complementary characteristics into one hybrid system. Usually this will involve coupling a high-energy storage technology with a high-power technology, which can lead to an improved lifetime and increased efficiency for the storage system[31]. Though important, hybrid energy storage systems have not received sufficient attention and merit increased focus for RD&D.

5.6 European Competences in Energy Storage

Chemical Energy Storage

Chemical storage is an area that has shown rapid development in Europe in recent years. Considerable funding from both the EU and its 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[32]. 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. Increasing energy density, methane, and liquid fuel synthesis is included in a number of P2G projects. This P2X scheme would allow energy storage in existing gas and oil storage facilities, whilst being compatible with current heating and propulsion technology.

Chemical storage is well suited to facilitate the integration of a large share of RES, which will play an increasingly important role in Europe. Countries like Germany have already identified that P2X has a great opportunity to decarbonise the transport sector and the German Federal Government opened a funding initiative in 2017 to support research and innovation in road and maritime applications. Air transport will also depend on liquid energy carriers with a very high energy density in the long run. First activities have been started throughout Europe to investigate the generation and utilisation of synthetic liquid hydrocarbons as jet fuel for aeronautics.

Chemical energy storage remains a largely European phenomenon and it reduces costly dependency on fuel imports from countries outside of the EU. Its industrial singularity and symbiosis with other major European economic sectors is fundamental for Europe's competitiveness and excellence. The European chemical storage industry is therefore expected to grow significantly.

31 Thilo Bocklisch: Hybrid Energy Storage Systems for Renewable Energy Applications, Energy Procedia 73, pp. 103–111, 2015.

32 US Department of Energy: Global Energy Storage Database, 2016. http://www.energystorageexchange.org/projects

Electrochemical Energy Storage

The European industry's position is strong in the most mature electrochemical storage technologies, such as Lead-acid[33], NaNiCl (known as ZEBRA batteries), and 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)[34] 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 has the opportunity 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, Italy, and the UK, although most of these projects are located in Japan and the United States. $Na/NiCl_2$ is mainly used in public transport and was first manufactured in the EU in 1999 and has since also been manufactured in the United States. Metal-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. 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.

Na-ion batteries are also considered a possible successor for Li-ion batteries due to significant cost reductions expected in the coming years. Other options such as the Mg battery, Mg-S, Al-battery, Zn-air and others are currently being explored. While there is continuous progress in all of these fields, none of them is already competitive to the performance of Li-ion technology. The first Na-ion cells are expected to be commercialised soon, and HONDA has announced the introduction of the first commercial Mg battery for 2019.

In summary, all of these materials will need significant improvements in cyclability and power density before they will be viable candidates to compete with Li-ion.

Finally, flow batteries are in the demonstration and early commercialisation phase. In Europe, flow battery research focuses on both small and large devices, especially for developing cost-effective new membranes and increasing the power density of the cell. There is an increasing number of companies' worldwide offering redox flow batteries to the market, many of which are located in Europe[35]. However, there is increasing competition from non-European companies and the world leaders in terms of installed capacity are located in Asia.

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.

33 European Commission: SET- Plan ACTION n°7 –Declaration of Intent: "Become Competitive in the Global Battery Sector to Drive E- Mobility Forward", 2016. https://setis.ec.europa.eu/system/files/action7_declaration_of_intent_0.pdf

34 Freedonia: World Lithium, 2015. http://www.freedoniagroup.com/industry-study/world-lithium-3331.htm

35 European Parliament: Energy Storage: Which Market Designs and Regulatory Incentives are Needed?, 2015.www.europarl.europa.eu/RegData/etudes/STUD/.../IPOL_STU(2015)563469_EN.pdf

Electrical Energy Storage
Supercapacitors

The first discoveries in this field were made in 1957. Since the early 1980s niche uses have been seen and a broader deployment of supercapacitors has accelerated over the last 20 years. Supercapacitors 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°C to +65°C) are well matched with existing grid assets. The deployment of supercapacitors in grid energy storage systems – as a stand-alone energy storage technology or hybridised with batteries – is rapidly growing.

Research and development activities are focused towards improving energy density of the core technology, developing miniaturised capacitors, and demonstrating power electronics that support the control and management of supercapacitors combined with batteries or another secondary energy storage technology. In Europe the main producers are based in Germany and France; however, worldwide 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 400kJ and Bi2212 material operating at 20 K[36] (-253.15°C). At the Karlsruhe Institute of Technology (KIT) in Germany, a hybrid concept with a SMES, in combination with hydrogen, has been studied in detail[37] 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.

In Spain, a consortium led by REESA built up two demonstrators in the context of the AMAS 500 project for grid quality operations. ICMAB-CSIC is designing and promoting a demonstrator for integration in the electronics for buffering of large capacity storage systems as electrochemical or cryogenic (LACAES) for petrochemical centres increasing their performances. Additionally, very recently, a new SMES project was launched in Italy with Columbus, ENEA, RES[38], 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.

36 A. Badel, P. Tixador, K. Berger and M. Deleglise: Design and Preliminary Tests of a Twin Coil HTS SMES for Pulse Power Operation", Supercond. Sci. Technol. 24, 055010, doi:10.1088/0953-2048/24/5/055010, 2011.
37 M. Sander, R. Gehring and H. Neumann: LIQHYSMES—A 48 GJ Toroidal MgB2-SMES for Buffering Minute and Second Fluctuations, IEEE Transactions on Applied Superconductivity, Vol. 23, No. 3, 2013.
38 Reliable Environmental Solutions.

Mechanical Energy 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 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[39] in Germany and the European project Advanced Adiabatic Compressed Air Energy Storage (AA-CAES)[40], 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 for electricity other than PHS currently available on a commercial scale in Europe.

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.

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.

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[41]. 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.

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39 Adiabatic Compressed Air Energy Storage for Electricity Supply (ADELE): Compressed Air Instead of a Pumped-Storage Power Plant, 2015. http://forschung-energiespeicher.info/en/projektschau/gesamtliste/projekt-einzelansicht//Druckluft_statt_Pumpspeicher/
40 CORDIS: Advanced Adiabatic Compressed Air Energy Storage (AA-CAES), 2005. http://cordis.europa.eu/project/rcn/67580_en.html.
41 Highview Power: Pre-Commercial LAES Technology Demonstrator, 2017. http://www.highview-power.com/pre-commercial-laes-technology-demonstrator/

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, flywheel projects are installed in France, United Kingdom, Germany, Spain, the Portuguese islands, and, in particular, in Ireland where a hybrid flywheel plant was built in 2015[42]. The Irish project (promoted by Schwungrad Energie[43]) is attracting interest from national grids across Europe, which plan to increase their renewable energy penetration in the years ahead[44],[45]. The flywheel project has received funding from both the European Commission and the Irish government.

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[46] (around 30% of global capacity) is in operation in the EU, representing 12% of total net electrical installed capacity in the EU[47]. By 2020, installed PHS capacity in Europe is expected to reach 47.8 GW, a rise of almost 16% in 10 years[48], since PHS is the most mature and cost-effective large-scale storage solution available in Europe today. The European 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[49].

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[50]. 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 (e.g. variable speed solutions are being developed to enhance the operational flexibility of PHS plants[51].

42 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.
43 Company website: http://schwungrad-energie.com/
44 Arthur Neslen: New Energy Storage Plant Could 'Revolutionise' Renewable Sector, The Guardian, 2015. https://www.theguardian.com/environment/2015/apr/08/new-energy-storage-plant-could-revolutionise-renewable-sector
45 Schwungrad: First Hybrid-Flywheel Energy Storage Plant in Europe announced in Ireland, 2015. http://schwungrad-energie.com/hybrid-flywheel-energy-storage-plant-europe-announced-ireland/
46 European Parliament: Energy Storage: Which Market Designs and Regulatory Incentives are Needed?, 2015.www.europarl.europa.eu/RegData/etudes/STUD/.../IPOL_STU(2015)563469_EN.pdf
47 U.S. Energy Information Administration (EIA): Total Electricity Installed Capacity, 2014. http://www.eia.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=2&pid=2&aid=7
48 eSTORAGE: Potential for Conversion of Classical PSP to Variable Speed Units in EU15, Norway and Switzerland, 2016. http://www.estorage-project.eu/wp-content/uploads/2013/06/EXTRACT-of-eStorage-D4.1-Potential-for-conversion-of-classical-PSP-to-variable-speed-units.pdf
49 DNV GL: Hydropower: Part of the Renewable Family, 2015. http://www.thehea.org/macro-economic-study-on-hydropower/
50 eStorage: eStorage Study Shows Huge Potential Capacity of Exploitable Pumped Hydro Energy Storage Sites in Europe, 2016. http://www.estorage-project.eu/wp-content/uploads/2013/06/eStorage-D4.2-press-release-FINAL.pdf
51 eSTORAGE: Potential for Conversion of Classical PSP to Variable Speed Units in EU15, Norway and Switzerland, 2016. http://www.estorage-project.eu/wp-content/uploads/2013/06/EXTRACT-of-eStorage-D4.1-Potential-for-conversion-of-classical-PSP-to-variable-speed-units.pdf

Thermal Energy Storage

The major driver for the development of thermal energy storage (TES) technologies has been the utilisation of solar thermal and geothermal energy resources for domestic heating and cooling as well as electricity production by concentrated solar power (CSP) plants. In these areas industrial companies supplying (mainly sensible) commercial TES systems have penetrated the European market reaching out for other world regions. European Commission's funding has been directed towards these major fields of application, resulting in sustainable capacity building of research units in numerous European countries. R&D covers the material, component as well as system level in order to achieve SET-Plan targets. Besides, several large national funding initiatives on energy storage have been launched in different European countries contributing significantly to the advancement of thermal energy storage technologies with a wider scope of applications also supporting industrial utilisation - namely the Helmholtz Programme "Storage and Cross-Lined Infrastructures"[52], the German Energy Storage Funding Initiative[53] and the Swiss Competence Centre "Heat and Electricity Storage (HaE)"[54]. On an international level, the IEA's TCP "Energy Storage through Energy Conservation" puts a strong focus on thermal energy storage and brings together experts from all over the world to gather their knowledge on this cross-cutting technology[55].

Sensible Heat Storage

At low temperatures different types of water storages are commonly used in Denmark, Sweden, the Netherlands, Norway, and Germany together with renewable solar or geothermal heat and electricity from photovoltaics in centralised and distributed energy systems[56], whereas in other European countries storage systems are still on a demonstration and pilot level. Denmark has an installed storage capacity of over 50 GWh in more than 3000 district heating plants. Six large installations for seasonal pit hole heat storage, with the largest holding over 200.000 m^3 of water, provide renewable heat at a system investment cost as low as 0.35 to 0.5 €/kWh. Improvements are mostly directed towards system aspects and standardisation to further bring down cost and enable multi-purpose operation within combined renewable thermal and electrical systems.

At higher temperatures, liquids such as thermal oil and molten salt or solids (i.e. ceramics, bricks, natural stones) are used as heat storage medium being applied in power plants and industrial processes. Cowper storages for steelmaking have been in use since the 1860s, whereas molten salt storage systems are a technology that has been commercialised in the last 20 years for application in concentrating solar thermal power plants. Main installations can be found in Spain and the US with around 30 GWh_{th} enabling dispatchability of renewable electricity generation from solar resources. Further applications in CAES or industrial processes are still in a development and early pilot stage, facing challenges in terms of fluid and thermo-mechanics, durability of the storage and building materials and cost-effective storage design.

52 Helmholtz Programme: Storage and Cross-Linked infrastructures. https://www.svi.kit.edu/73.php
53 German Energy Storage Funding Initiative. http://forschung-energiespeicher.info/en/waerme-speichern/ueberblick/
54 Swiss Competence Center for Heat and Electricity Storage. http://www.sccer-hae.ch/
55 IEA TCP Energy Conservation through Energy Storage. https://iea-eces.org/
56 IRENA: Thermal Energy Storage Technology Brief, 2013. https://www.irena.org/DocumentDownloads/Publications/IRENA-ETSAP%20Tech%20Brief%20E17%20Thermal%20Energy%20Storage.pdf

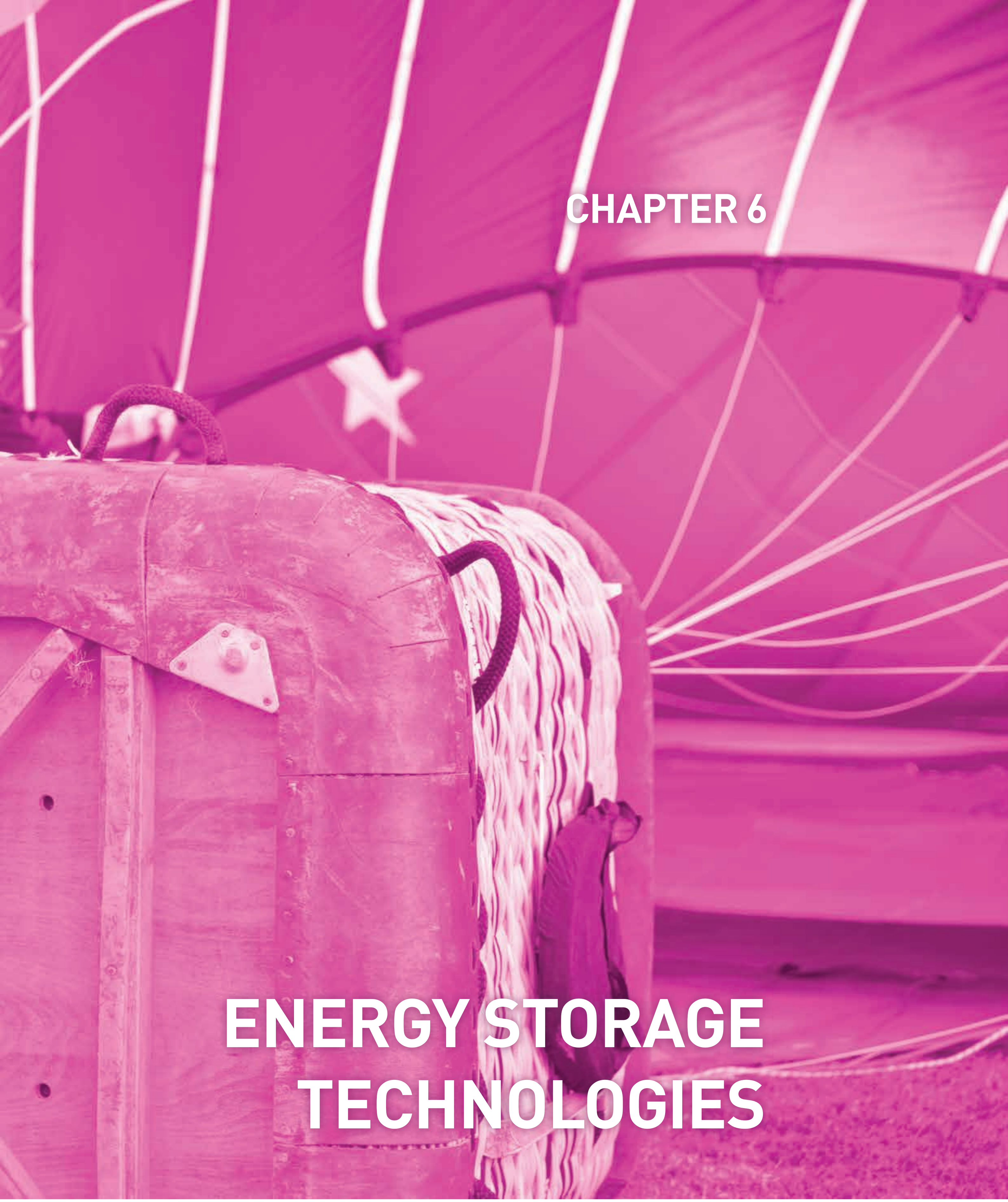
Latent Heat Storage

Micro-encapsulated, mostly organic phase change media (PCM) are being used commercially in latent heat storage enhanced building materials, which offer substantially increased comfort[57]. Besides, low-exergy systems utilise low-temperature latent heat storages for cooling applications in buildings. Ice storages have a long tradition since the 1930s and can nowadays also be used for peak-shifting in combination with cooling applications[58]. At higher temperatures latent heat storage is still on a lab-scale and demonstration level with salt mixtures or metal alloys being used as PCM. The largest unit currently under construction is a 6 MW/1.5 MWh storage unit that will be implemented in a cogeneration plant in Germany to provide superheated steam at 305°C[59]. Several research institutions in Europe are working on PCMs and slurries and passive as well as active storage concepts to improve heat transfer and stabilise the power level during discharging to bring down cost and increase performance of this technology.

Thermochemical Heat Storage

Europe has been a pioneer in terms of thermochemical energy storage (TCS). The first TCS studies were published in the 1970s by Swedish and Swiss researchers[60]. In recent years, thermochemical heat storage has seen increased interest with fundamental research being done on various reaction systems and storage materials to take advantage of the high storage densities and loss-free option for long-term storage. Specifically designed storage reactors and concepts remain largely at an experimental stage. European funding has been directed towards seasonal storage in decentralised units[61] as well as thermochemical storage for application within CSP plants[62],[63],[64]. These initiatives are complemented by national activities in numerous European countries as well as in the US and Asia including industrial involvement even at this early stage of development. Sorption storage systems are slightly more developed with the exception of sorption heat pumps which have been fully commercialised. Due to their high storage density, the application of thermochemical systems in the thermal management of vehicles is being considered as well. Another specific feature of chemical reactions is the possibility for thermal upgrading of waste and process heat streams, which attracts large industrial interest for different temperature levels.

57 BASF website: www.micronal.de
58 Evapco website: http://www.evapco.eu/products/thermal_ice_storage
59 The TESIS project: Project Single View - Forschung Energiespeicher
60 Wettermark G, Carlsson B, Stymne H.: Storage of Heat: A Survey of Efforts and Possibilities, Swedish Council for Building Research, 1979.
61 The COMTES project: http://comtes-storage.eu/
62 The TCSPower project: http://www.tcs-power.eu/home.html
63 The StoRRe project: http://www.storre-project.eu/
64 The Restructure project: http://cordis.europa.eu/result/rcn/144104_en.html



CHAPTER 6

ENERGY STORAGE TECHNOLOGIES

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 low-carbon electricity into hydrogen, with the possibility to combine it with CO_2 to synthesise energy-rich gases (Power-to-Gas) and liquids (Power-to-Liquid) which can be used as fuels or to combine with nitrogen to produce chemicals, such as ammonia.

a) Hydrogen

Electrolyser technology uses electricity to split water (H_2O) 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 electrolysers based on solid oxide technology, which can make use of CO_2 and produce syngas or synfuels. In addition, plasma-chemical conversion or plasmolysis to split CO_2 or water through vibrational excitation of the molecules in thermal non-equilibrium has been shown to be possible. Another development is photo-electrolysers that can direct H_2 production from sunlight.

Hydrogen plays a central role in chemical energy storage[65]. 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, internal combustion engines and turbines, direct steam generation, catalytic combustion, and fuel cells) 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. Moreover, it is one of the very few options to store energy over days and weeks, e.g. in solution-mined salt caverns, which has been tested in the US for decades and is considered as a safe and cost-effective solution for large-scale storage of H_2.

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 industry. These are mainly methane (CH_4), methanol (CH_3OH), and ammonia (NH_3). Further synthesis would allow production of transportation fuels such as dimethyl ether (DME) and kerosene. These fuels are of non-fossil origin as they are produced from feedstock, air, and water. Conversion into synthetic hydrocarbons not only allows long-term large-scale energy storage, it also enables a carbon neutral fuel cycle, essential for decarbonising the transport sector.

65 Indeed, hydrogen is the only realistic chemical storage option (except perhaps ammonia) to avoid CO2 emissions for all end users. Other chemical carriers should therefore be considered primarily for systems including CO2 capture and storage.

Maturity of Technology Chain Components

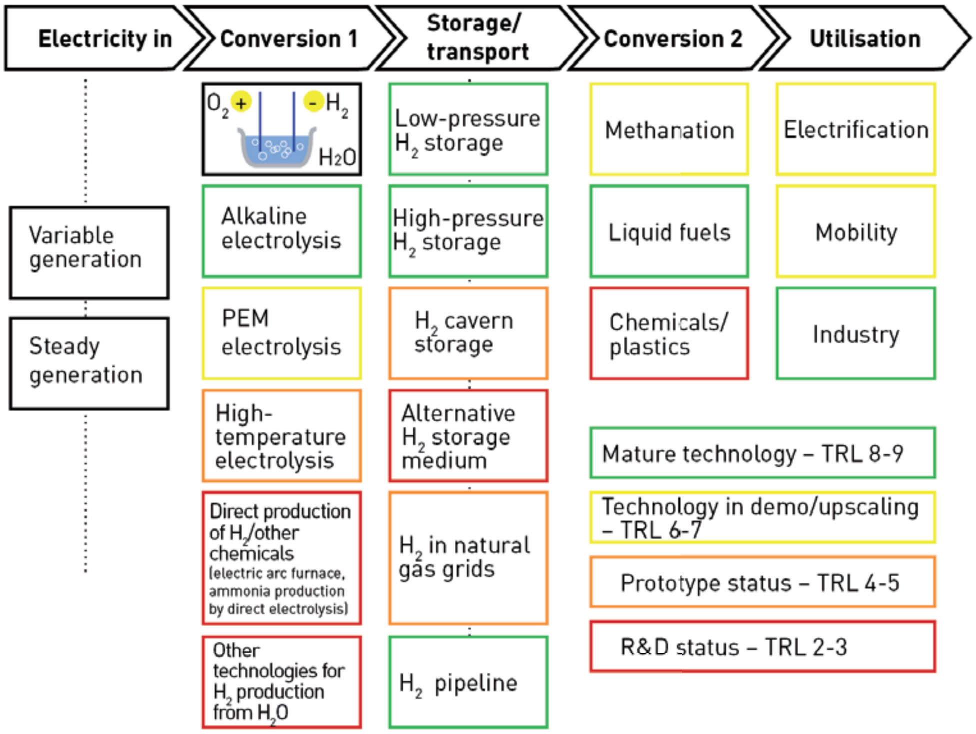


Figure 5: Technical maturity of chemical storage components. Adapted from Siemens, 2012.

Applications

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

- CO_2 emissions reduction
- Energy security (indigenous electricity conversion into methane, liquid hydrocarbon fuel)
- Energy resilience (integration of 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 energy arbitrage
- Seasonal energy storage (TWh scale)
- Electrification in the chemical industry by providing hydrogen carriers (H_2, NH_3) or C1 building blocks (methane, methanol)
- Indirect electrification of aviation, marine sector and transport by cars and trucks by synthetic fuels based on electricity

- Grid services (voltage, frequency stability): electrolysers are fast-reacting devices, once a voltage is applied above the equilibrium voltage. Existing experience with electrolysers demonstrates that they have the ability to react within a second or lower upon changes in electricity supply or demand, both up and down. Electrolysers are therefore well suited for provision of many types of ancillary services for the future electrical grid with a high penetration of renewables including primary operational reserves. Cold-start duration depends on electrolyser technologies and varies from tens of minutes to hours for electrolysers operating at temperatures highly above ambient.

SET-Plan Targets[66] for Electrolysis and Hydrogen Storage Technologies for 2030 and beyond

Table 1: SET-Plan Targets Alkaline Technology.

Property	State-of-the-art	Target 2020-2030	Ultimate goal
Operating current density (A/cm^2)	0.2–0.5	0.1–1	0–2
Operating temperature (°C)	ambient – 120	ambient - 150	ambient - >150
Operating pressure (bar)	1-200	1-350	1-700
Durability (h)	10^5	> 10^5	> 10^5
Cyclability	poor	improved	high
Production capacity of electrolysis units (Unit size 1 MW)	1-100 kg/hour (≈ 10-1000 Nm^3/hour)	> 100 kg/hour (≈ 1000 Nm^3/hour)	> 1000 kg/hour (≈ 10 000 Nm^3/hour)
Non-energy cost (€/kg H_2)	<5	2	1

Table 2: SET-Plan Targets PEM Technology.

Property	State-of-the-art	Target 2020-2030	Ultimate goal
Operating current density (A/cm^2)	0 – 2	0 – 2	0 – 5
Operating temperature (°C)	50-80	80-120	100-150
Operating pressure (bar)	1-50	1-350	1-700
Durability (h)	10^4	$10^4 – 5 \cdot 10^4$	> 10^5
Production capacity of electrolysis units	1-30 kg/hour (≈ 10-300 Nm^3/hour)	> 30 kg/hour (≈ 300 Nm^3/hour)	> 100 kg/hour (≈ 1000 Nm^3/hour)
Energy efficiency (kWh/kg H_2 at 80°C, 1 A.cm^{-2})	56	< 50	48
Non-energy cost (KWh/kg H_2)	5	2	1

66 Commission Staff Working Paper: Materials Roadmap Enabling Low Carbon Energy Technologies, 2011. http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

Table 3: SET-Plan Targets Solid Oxide Technology.

Property	State-of-the-art	Target 2020-2030	Ultimate goal
Operating temperature (°C)	800-950	700-800	600-700
Operating pressure (bar)	1-5	1-30	1-100
Operating current density (A/cm²)	0–0.5	0–1	0–2
Area specific resistance (Ω.cm²)	0.3-0.6	0.2–0.3	
Enthalpic efficiency	100% at 0.5 A/cm²	100% at 1 A/cm²	100% at 2 A/cm²
Durability (h)	10^3	10^4	10^5
Electrical modulation	Unknown	0-100	0-100
Load cycles	Unknown	10,000	> 10,000
Start-up time (h)	12	1-6	< 1-6
Production capacity of electrolysis units	<1 kg/hour (≈ 10 Nm³/hour)	10 kg/hour (≈ 100 Nm³/hour)	100 kg/hour (≈ 1000 Nm³/hour)
Non-energy cost (€/kg H_2)	5	2	1

Table 4: SET-Plan Targets Plasmology CO_2.

Property	State-of-the-art	Target 2020-2030	Ultimate goal
Power density (W/cm³)	10	100	1000
Enthalpic efficiency (enthalpy/power in)	50%	70%	80%
Operating temperature (°C)	ambient	ambient - 150	ambient - >150
Operating pressure (bar)	0.2-0.5	0.5 - 1	1 – 1.2
Durability (h)	10^5	> 10^5	> 10^5
Separation effluent gases in constituents	poor	improved	high
Use of scarce materials	None	None	None
Production capacity (kg/hr)	1	10	> 100
Non-energy cost (€/kg CO)	<1	0.1	0.05

Hydrogen Storage Technologies

Table 5: SET-Plan Targets Hydrogen Storage Technologies.

Storage Technology	Volumetric density (kg H_2/m^3)	Gravimetric density (reversible) (wt %)	Operating pressure (bar)	Operating temperature (K)	Cost* ($ / kg H_2)
Compressed gas (H_2)[70]	17 - 33	3 - 4.8 (system)	350 & 700	ambient	400-700*
Cryogenic (H_2)[71]	35 - 40	6.5 – 14 (system)	1	20	200-270*
Cryo-compressed (H_2)	30 - 42	4.7 – 5.5 (system)	350	20	400
High pressure - solid	40	2 (system)	350	243 – 298	
Sorbents (H_2)[72]	20 - 30	5 – 7 (material)	80	77	
Metal hydrides (H)[73]	< 150	2 – 6.7 (material)	1 – 30	ambient – 553	>500
Complex hydrides (H)[74]	< 120	4.5 – 6.7 (material)	1 - 50	423 – 573	300-450*
Chemical hydrides (H)[75]	30	3 – 5 (system)	1	353 – 473	160-270**

* 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[67] 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[68].

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), developing electrolyser technology to address the challenges of integrating variable RES, and better incorporating electrolyser technology with downstream processes with the overall objective of decreasing the

67 The establishment of demonstrators is in some cases hampered by the lack of incentives and insufficient regulatory framework for energy storage, as will be discussed in Chapters 7 and 8.
68 ARPA-E: Refuel FAQ, 2016. http://arpa-e.energy.gov/?q=pdfs/refuel-sbirsttr-de-foa-0001563

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, optimise temperature with respect to catalyst activity and material thermal resistance requirements 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 CO_2 to: ammonia, methane, methanol, dimethyl-ether, oxy-methylene ether (OME), synthetic kerosene, formic acid, and other chemicals;
    b. The integration of these processes with upstream (renewables, electrolysers, CO_2 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.
3. Starting-Lighting-Ignition batteries used for automobile devices: segment dominated by lead-based batteries.

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. Power grid 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 can be 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 in external circuit – electric current. Primary elements of a cell include the container, two electrodes (anode and cathode), an electrolyte material (liquid or solid), and a separator, which prevents a short contact of the electrodes. The electrolyte is in contact with the electrodes. Current is created by the oxidation-reduction reactions between the cell electrolyte and electrodes. When a battery discharges through a connected load, the electrolyte that is near one of the cell electrodes causes release of electrons (oxidation) by dissolving the electrode material. Meanwhile, ions near the other cell electrode accept electrons (reduction) to complete the process. The process is reversed to charge the battery.

The conventional battery configuration is based on electrochemical charge/discharge reactions that occur between a positive electrode (on which the reduction occurs, the cathode) and a negative electrode (on which oxidation occurs, the anode) located in a cell. The electrodes, immersed in an electrolyte, are separated by a permeable membrane which allows for ionic flow between them.

Another configuration is known as redox flow batteries (RFB), which use two electrolytes (liquid or a mix of liquid and gas) – one in high oxidation state and one in low oxidation state - as energy carriers. The electrolytes are divided using a separator, such as an ion-selective membrane, which under charging and discharging conditions allows selected ions to pass and complete chemical reactions at the cell level. The RFB technology represents a variety of combinations of electrolytes. One of the fundamental differences between flow batteries and other electrochemical storage technologies is that power (kW) and capacity (kWh) are de-coupled and as such flow batteries allow free configuration of power and capacity: the battery power is determined by the total membrane surface area, and the capacity by the volumes of the active materials.

Maturity of Technologies

Of the current installed worldwide grid-connected energy storage capacity, estimated at about 171,060 MW in 2016, electrochemical storage makes up approximately 1,639 MW[69]. 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.

Status	Energy Storage Technology
Mature	Lead-acid, Ni-Cd (nickel cadmium), NiMH (Nickel–metal hydride)
Commercial	Li-ion, Lead-acid, NaS (sodium-sulphur) and NaNiCl2 (Zebra), Li-ion capacitors, ZnBr (zinc bromine), Va (vanadium) flow batteries, Zinc-air, Li-polymer
Demonstration	Advanced lead-acid, Li-ion, Na-ion, HBr (hydrogen bromine) flow batteries, LiS
Prototype	FeCr (iron chromium), Li-ion capacitors
Laboratory	Advanced Li-ion, new electrochemical couples (other Li-based), liquid metal batteries, Mg-based batteries, Li-air and other Metal-air batteries, Al batteries, nonaqueous flow batteries, solid-state batteries, batteries with organic electrodes
Idea, concept	Solid electrolyte Li-ion batteries, rechargeable Me-air batteries (Mg-air, Al-air and Li-air)

69 US Department of Energy: Global Energy Storage Database, 2016. http://www.energystorageexchange.org/projects/data_visualization

The battery market is currently dominated by lead-based batteries but lithium-based batteries represent the highest growth rate, as shown in figure 7.

The global battery market was valued at $65 billion in 2015 (pack level) with a 5% average annual growth between 1990 and 2015[70].

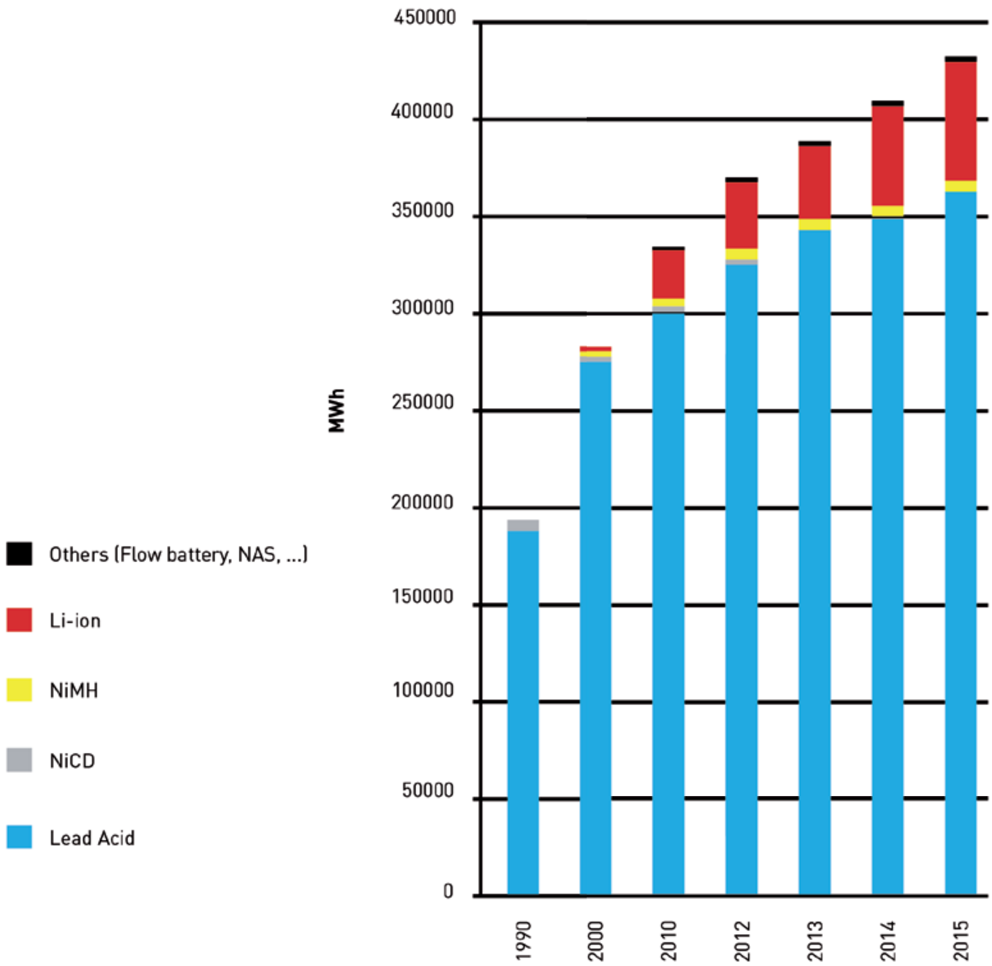


Figure 6: Battery market growth (MWh) 1990-2015, Avicenne Energy, 2016.

70 Avicenne Energy: Worldwide Rechargeable Battery Market 2015-2025, 2016. 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 8:

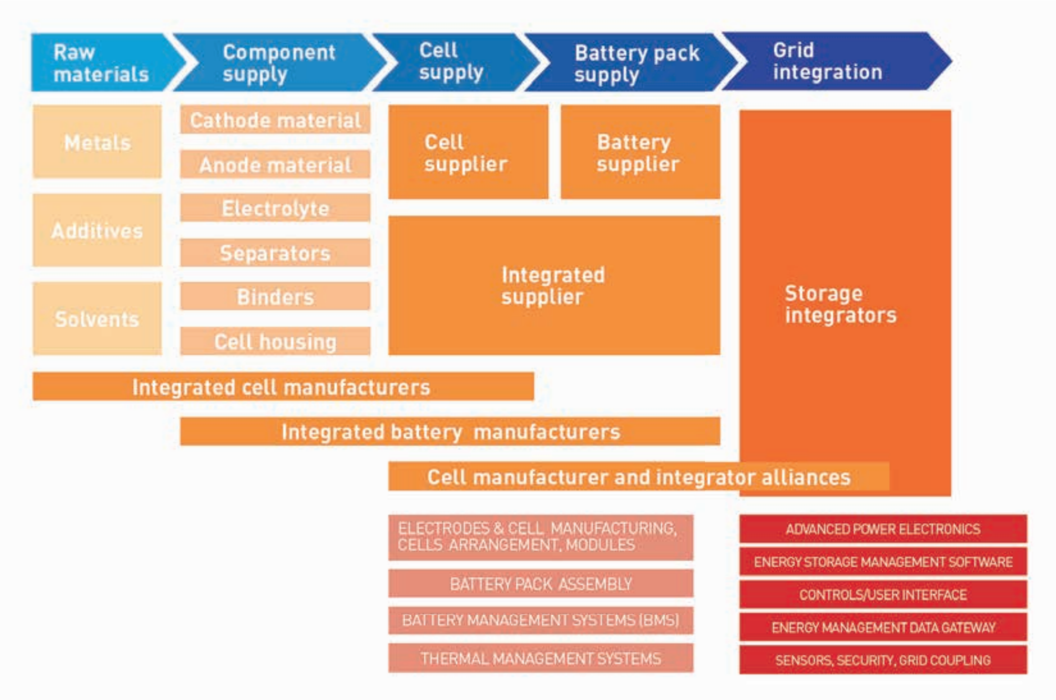


Figure 7: Compilation by EMIRI, EUROBAT, EASE, and Technofi, 2016.

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[71]
- Advanced materials and component suppliers (anode active material, cathode active 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 especially valuable for the European battery industry.

71 Securing reliable and unhindered access to certain raw materials is a growing concern for the EU, which relies on imports for materials including lithium, nickel, chromium, and magnesium (Source: European Commission: Critical Raw Materials, 2017). https://ec.europa.eu/growth/sectors/raw-materials/specific-interest/critical_en. Significant growth in the battery industry could lead to supply shortages of raw materials for the production of batteries. At the same time, prices for Lithium as a raw material have been showing a steep increase. The significant decrease in prices for Li batteries from the past years could at one point come to an end, or even reverse.

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. For the mid- and long-term, carmakers have predicted a shortage of critical elements such as cobalt, which plays an essential role in current and next generation Li-ion batteries in BEV. This shortage is predicted starting from 2023 – 2025 and materials research directions may have to be adjusted accordingly.

This LCOSE calculation, which considers capex, lifetime, capacity and efficiency, forms an objective way to compare the large variety of technologies with respect to ROI, and determines as such the economic viability of a certain storage technology. A general LCOSE is difficult to calculate, however, as the levelised cost depends on the application or set of application(s) an energy storage device is providing[72].

Some battery technologies, such as Li-ion, are expected to benefit from the R&D and industrial investments made for the automotive and mobile communication sectors. The rapidly decreasing costs for EV battery packs (as seen in figure 9) are expected to have an impact on the energy storage batteries sector as a whole. Advanced lead batteries, with high-power performance and more lifecycles than the conventional lead cells, given their low upfront costs and vast expertise in off-grid PV applications, are playing a competitive role in the emerging utility scale energy storage markets and further research on this technology is needed.

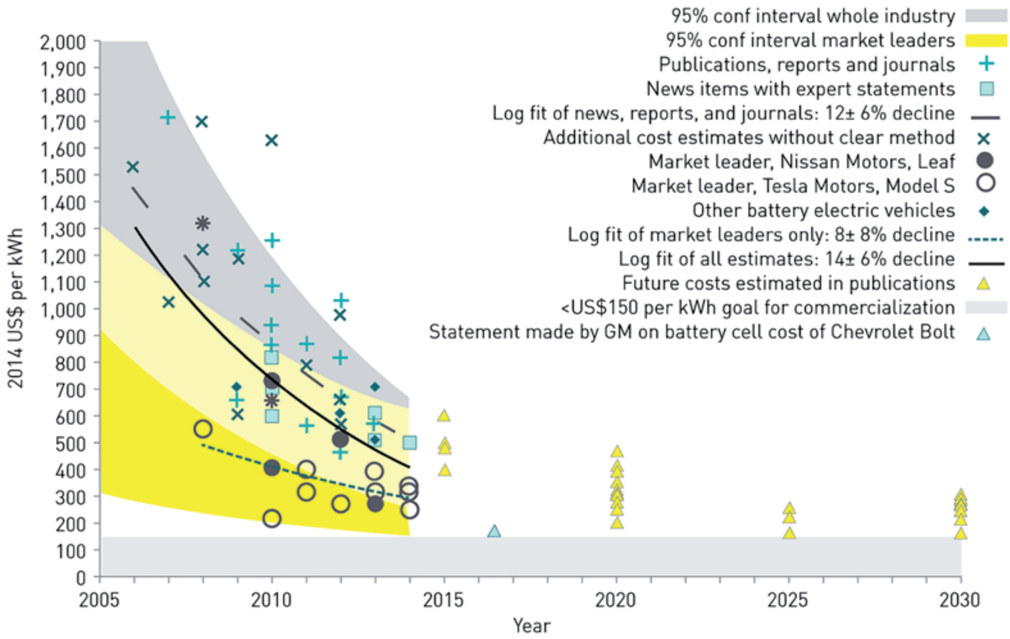


Figure 8: Cost estimates and future projections for electric vehicle battery packs, measured in US $ per kilowatt hour of capacity. Each mark on the chart represents a documented estimate reviewed by the study. Source: Nykvist et al. (2015)[73].

72 Lazard: Lazard's Levelized Cost of Storage – Version 2.0, 2016. https://www.lazard.com/perspective/levelized-cost-of-sto-rage-analysis-20/

73 Björn Nykvist and Måns Nilsson: Rapidly Falling Costs of Battery Packs for Electric Vehicles, Nature Climate Change 5, pp. 329–332, 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).

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[74].

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

Storage Segment	Storage Type	Storage Duration[I]	Lead-acid	Ni-Cd	Li-ion	NaS	$NaNiCl_2$	Flow
Fast-acting storage	Power quality	<1 min	🟢	☹	🟢	🟠	🟠	🟢
	Power system stability	1 – 15 min	🟢	🟢	🟢	🟢	🟢	🟢
Power storage		15 – 60 min	🟢	🟢	🟢	🟢	🟢	🟢
Energy storage	Daily	6 h	🟢	🟠	🟢	🟢	🟢	🟢
	Weekly	30 – 40 h	🟠	☹	☹	🟢	🟢	🟢
	Monthly	168-720 h	☹	☹	☹	🟠	🟠	🟠

I: This refers to the length of the service provision.

🟢	Very suitable
🟠	Less suitable
☹	Unsuitable

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 8-14% per year over the past 10 years, a €1 billion market for decentralised battery storage is expected to develop in the coming decades[75]. 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.

74 RSEview: L'accumulo di energia elettrica, Il Melograno Editore, 2011.
75 Björn Nykvist and Måns Nilsson: Rapidly Falling Costs of Battery Packs for Electric Vehicles.

SET-Plan Targets[76] 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 stationary battery systems in 2030:

- System cost < €150/kWh (for a 100 kW 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 updated to reflect recent developments in battery technologies. Due to the difficulty of obtaining recent and comparable data covering all aspects of these many different technologies, the table is incomplete with respect to some electrochemical storage technologies. Nonetheless, the table is a good starting point to identify the gaps between current performance and the 2030 targets.

Table 8: Targets for electrochemical storage to support the SET-Plan.

Technologies	Now	2030
Lead-based Energy cost	< 120-200 €/kWh or << 0.1-0.15 €/kWh/cycle	< 100-75 €/kWh or << 0.08-0.04 €/kWh/cycle
Temperature operating range (stationary applications):	-30 to +50ºC	-30 to +50ºC
Specific performances:	25-50 Wh/kg and 60 to 140 Wh/L	40-60Wh/kg and 140-250 Wh/L
Cycle life:	> 2,000 (80% DoD) combined with long calendar life of 20+ years	> 3,000 cycles (at 80% DoD) -> 10,000 cycles (at 60% DoD, in specific cases at 80% DoD)
Li-ion (cell level)		
Specific energy	274 Wh/kg[II]	320 Wh/kg
Energy density	700 Wh/l	800 Wh/l
Cost	250 €/KWh	100 €/kWh
Power	3 000 W/kg	10 000 W/kg
Lifetime	5000 cycles (C anode), 10,000 cycles (Li-ion titanate)	10 000 cycles (C anode), 60,000 cycles (Li-ion titanate)
Safety:	High stability	No hazard
Va Flow Batteries		
Energy cost	400 €/kWh	Energy cost <100 €/kWh
Power cost	600 €/kW	Power cost <150 €/kW
Lifetime	10-20 years (>10,000 cycles)	

76 Commission Staff Working Paper: Materials Roadmap Enabling Low Carbon Energy Technologies, 2011. http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

HBr Flow Batteries:		
Energy cost	80 €/kWh	< 50 €/kWh
Power cost	250 €/kW	<100 €/kW
Lifetime	10,000 cycles (demonstrated)	50,000 cycles
Safety	Not flammable	
LCOSE	€0,05/kWh/cycle	€0,025/kWh/cycle
Depth of Discharge	90%, not related to life time	90%, not related to life time
High temperature: (Sodium-based cell level)		
Specific energy	150 Wh/kg	300 Wh/kg
Energy density	240 Wh/kg	400 Wh/l
Energy Cost	€250/kWh	150 €/kWh
Cycle life	4,500 cycles	10,000 cycles
Na-ion		
Specific Energy	90 Wh/kg (Aquion)	120-140 Wh/kg
Energy cost	€240/kWh (Aquion)	<€120 /kWh max
Lifetime	>5000 cycles	
Depth of Discharge	80%	
Metal-air Systems:		
Zn-air	$ 160/200/kWh for a 1 MW/4 MWH system (EOS)	?
Li-air	700Wh/kg (Li air Polyplus) 150 cycles[III]	>500Wh/kg, 300-500 €/kWh 3000 cycles
Li-S:		
Specific Energy	120 Wh/kg, 1 400 cycles at system level (48V/3 kWh: Oxis) or 350 Wh/kg, 100 cycles at cell level (Oxis)	400 Wh/kg , 3000 cycles at cell level
Energy cost		150 €/kWh

II: Achieved for consumer cells (18650) with limited cycle life time. Industrial cells achieve about 170 Wh/kg today.

III: In air with 17% humidity. Source: J. Amici et al: O2 Selective Membranes Based on a Dextrin-Nanosponge (NS) in a PVDF-HFP Polymer Matrix for Li–air Cells, Chem. Commun., p 52, 2016.

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

- Advanced lead technology: compared to conventional lead batteries, advanced lead batteries have already improved cycle life time and improved performances at partial state of charge. Research is needed to further improve the cycle life time and operation at partial state of charge without increasing investment costs (€/kWh). The specific power density can be significantly improved, e.g. by thin plate technology, innovative grid material as well as advanced additives, in order to become more competitive in applications with high rate charge and discharge (1 to 15 minutes as shown in table 7). Another research domain for advanced lead batteries is to improve the charge efficiency in parallel with the high charge acceptance.
- High temperature battery technology (sodium based): although the worldwide reserve power markets already show high interest in the technology thanks to the high energy density and a wide range of operation temperature, further research will address next sodium based battery generation, based on a new cells, able to ensure significant improved and suitable performance for energy driven storage application. More power in charge, longer cycle life, and even more energy density will match with a simplified design and lean industrial process. Strong cost reduction and huge increase in installed production capacity are in progress.

- Li-ion technology: although L-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 would be the use of second hand batteries provided by the transport sector; however, this would require a new regulatory framework. 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 could lead to improvements in safety, once challenges related to dendrite formation are overcome.

- Mg and Mg-S technology: current Mg systems still suffer from comparably low discharge voltages and low energy efficiency. There is technical progress on Mg-S in Germany, where a consortium will fabricate and test the first 20 Ah cells in 2018.

- Metal-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 lifetime, 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. In addition, all components of a RFB are recyclable, even the metals, and there are no explosive or flammable materials. For Vanadium Redox flow batteries, there are two key challenges to be addressed: substantial cost reduction of the flow battery systems (reactants and electrolytes, membrane and materials), better life time of the membrane, and possibly improvements in power and energy density. However, the main challenge of all redox flow technologies is to reach a volume level that will allow for economies of scale and achieving a competitive LCOSE.

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[77] 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.

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 5 V)

77 Keeping in mind the risks associated with a reliance on raw materials, many of which have to be imported to the EU.

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. The product end of life and the circular economy with a given minimum percentage of materials to be reused or recycled should be taken into account for developing complete new electrochemical systems. 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 200 €/kWh.

6. Intensive research efforts should be carried out at the grid integration level in order to increase battery lifetimes, decrease storage system costs, and 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 the cell, pack, and system level.

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

9. With respect to the long-term sustainability, battery recycling will become an issue when batteries are produced at rates of hundreds of GWh/year, as is projected for 2030. This will be particularly relevant in technologies where recycling is not sufficiently developed yet, such as Li-ion.

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 million 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. Given the diversity of electrochemical technologies available for energy storage applications, an EU-wide demonstration programme (assessing all technologies across the different energy storage applications/needs) would also be desirable.

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 and the pore size distribution in ECs 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 ECs because of the use of a high surface area, porous carbon-based electrode material.

While supercapacitors have very high specific power (10-20 kW/kg) relative to batteries, they have a low specific and volumetric energy density (<8 Wh/kg). One related technology 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 super capacitor-type positive electrode, while the negative electrode contains a lithium intercalation compound (battery-type electrode). State-of-the-art technology indicates a three- to five-fold increase in energy density relative to a supercapacitor, with a similar discharge profile and only slightly lower 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 12 kV and distribution voltages up to 1500 V. 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. Tertiary frequency control: this is the generation capacity that a utility holds in reserve to prevent service interruptions if a generator fails. A supercapacitor system can be built to supply power during the interruption, until quick-start diesels begin to supply power. A typical specification is 20 MW to 100 MW and 300 MJ to 1500 MJ.
3. Secondary 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. Supercapacitors 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[78]

Tables 9 and 10: SET-Plan targets for supercapacitor* technologies towards 2030 and beyond.

Table 9: Technical targets.

	Current performance	Target 2030	Target 2050
Voltage	3.0 Volt	4.0 Volt	4.5- 5 Volt
Energy density	4-8 Wh/kg EDLCs	50Wh/kg	75 Wh/kg
	15-30 Wh/kg for LCAPs		
Power density	»10-20kW/kg (1-5s)	»40kW/kg (1-5s)	»60kW/kg (1-5s)
Specific capacitance	6F/g	50 F/g	ca. 600F/g
Cyclability	500k – 1M cycles	1.5M cycles	> 2M cycles
Temp Low	T = -40°C	T = -40°C	T= -40°C
Temp High	T= 65°C	T= 100°C	T= 125°C

Tabla 10: Economic targets.

	Current	Target 2030	Target 2050
€/W	0,3 €/W (cell basis)	0,2€/W (cell basis)	0,05€/W (cell basis)
€/F	0.015 c€/F	0.005 c€/F	0.002 c€/F

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

78 Commission Staff Working Paper: Materials Roadmap Enabling Low Carbon Energy Technologies, 2011. http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

Gaps between Targets and Present Performance

ECs are interesting for their capacity to store very high energy 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 practical 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[79]. 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.

Research Priorities

The following topics are key research priorities for ECs over the next decades:

1. Finding cost-effective 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 30-40 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. Research into hybrid systems – coupling batteries and supercapacitors into one storage system (not necessarily Li-ion capacitors) – could also prove valuable.
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.
5. Research on solid electrolytes may open new possibilities for ECs by simplifying the manufacturing procedure using roll-to-roll methods, by increasing safety and stability by eliminating risk of leakage, and also by opening the possibility to make ECs with enhanced mechanical properties.

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 10 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.

79 Navigant Research, 2016.

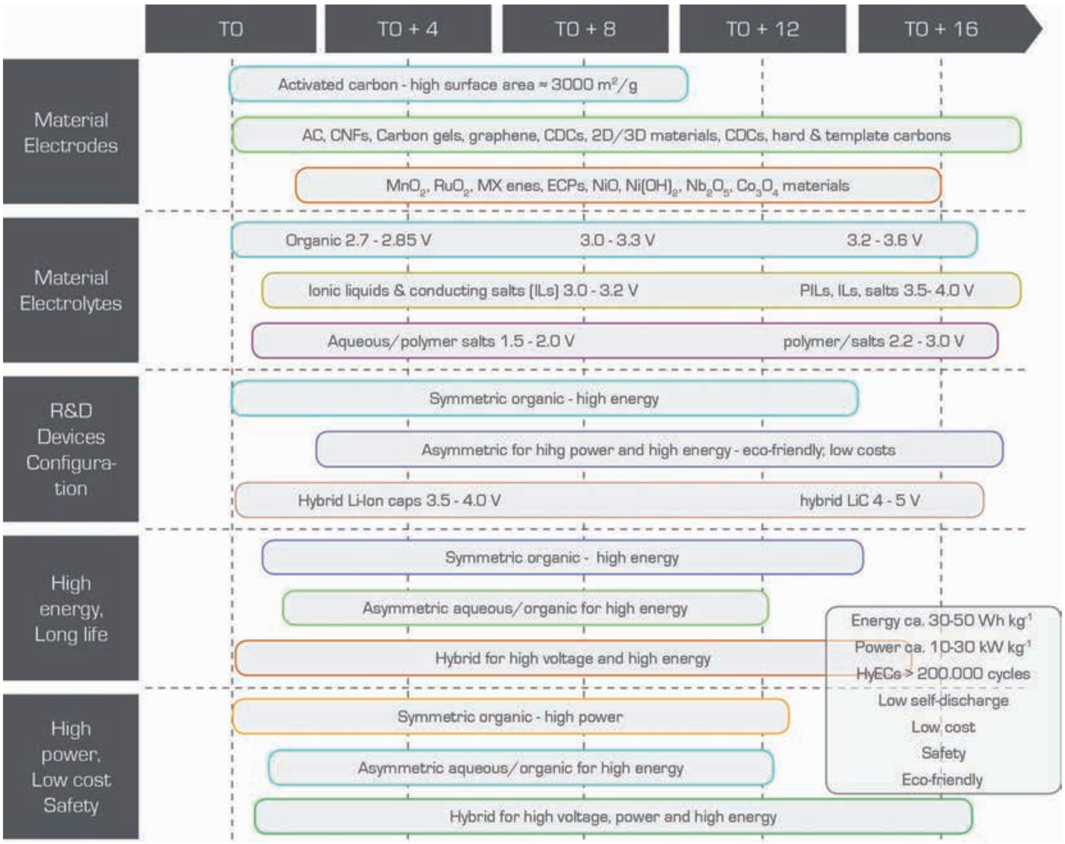


Figure 9: Tentative Roadmap for supercapacitors with vision to 2030. Prepared by CNR-ITAE based on several sources[80].

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 programme 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.

80 P. Staiti, A. Arenillas, F. Lufrano, J.A. Menendez, J. Power Sources 214, 137, 2012. Q. Gao, et al., Energy Environ. Sci. 5, 9611, 2012. S. Makino, et al., RSC Advances, 2, 12144, 2012. K. Naoi, et al. Energy Environ. Sci. 5, 9363, 2012.

Superconducting Magnetic Energy Storage (SMES)

Introduction

SMES has been of scientific interest for years[81],[82],[83],[84],[85] and still needs 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 (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, long-term energy supply based on liquefied hydrogen (LIQHYSMES), (see figure below) has been proposed which combines the use of LIQuid HYdrogen (LH_2) with SMES. The LIQHYSMES Storage Unit (LSU) as the core element integrates the H_2 liquefaction part, the LH_2 storage tank and the SMES cooled by the LH_2 bath. This allows jointly utilising the cryogenic infrastructure and drastically reducing the otherwise significant H_2 liquefaction losses and the cost.

81 Boenig H.J., Hauer J.F.: Commisioning Tests of the Bonneville Power Administration 30 MJ Superconducting Magnetic Energy Storage Unit, IEEE Trans. Power Apparatus and Systems, vol. PAS-104, No 2, DOI: 10.1109/TPAS.1985.319044, 1985.
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84 H. Salbert, D. Krischel, A. Hobl, M. Schillo, N. Blacha, A. Tromm, W. Roesgen: 2 MJ SMES for an Uninterruptible Power Supply, IEEE Transactions on Applied Superconductivity, Volume: 10, Issue: 1, 2000 , DOI: 10.1109/77.828346.
85 T. Katagiri, H. Nakabayashi, Y. Nijo, T. Tamada, T. Noda, N. Hirano, T. Nagata, S. Nagaya, M. Yamane, Y. Ishii, T. Nitta: Field Test Result of 10 MVA/20 MJ SMES for Load Fluctuation Compensation, IEEE Transactions on Applied Superconductivity, Volume: 19, Issue: 3, DOI: 10.1109/TASC.2009.2018479, 2009.

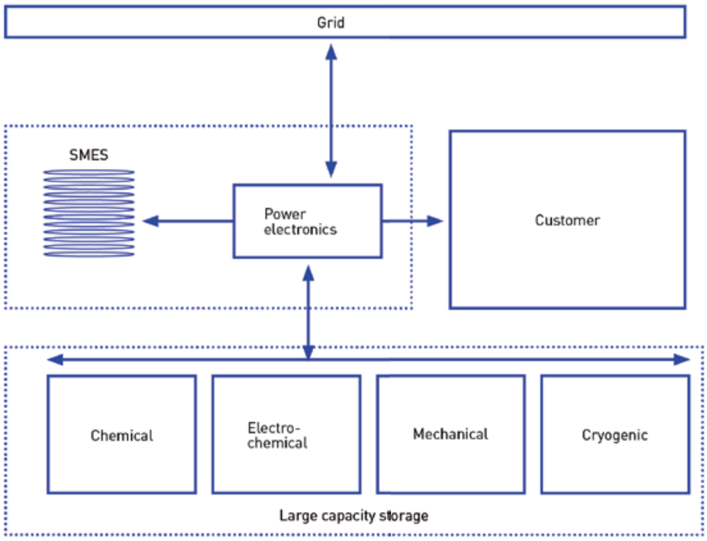


Figure 10: SMES buffering of mechanical, chemical, electrochemical or cryogenic Energy Storage Systems.

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.

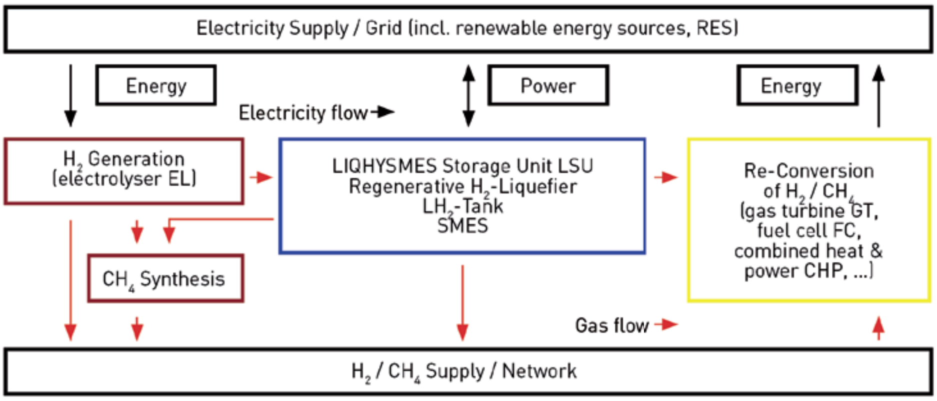


Figure 11: LIQHYSMES Storage Unit based on hydrogen for long term energy storage and SMES for short term storage[86].

86 M. Sander, R. Gehring, H. Neumann: LIQHYSMES—A 48 GJ Toroidal MgB2-SMES for Buffering Minute and Second Fluctuations, IEEE Transactions on Applied Superconductivity, Volume: 23, Issue: 3, DOI: 10.1109/TASC.2012.2234201, 2013.

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[87]. 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[88]. 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 2 G 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 or -223,15°C), 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[89] 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[90],[91] for different combinations but not more than a proof of concept and small laboratory experiments on a TRL of 3 have been 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

87 T. Katagiri, H. Nakabayashi, Y. Nijo, T. Tamada, T. Noda, N. Hirano, T. Nagata, S. Nagaya, M. Yamane, Y. Ishii, and T. Nitta: Field Test Result of 10 MVA/20 MJ SMES for Load Fluctuation Compensation, IEEE Transactions on Applied Superconductivity, Volume: 19, Issue: 3, pp. 1993-1998, DOI: 10.1109/TASC.2009.2018479, 2009.

88 Shigeo Nagaya, Naoki Hirano, Toshio Katagiri, Tsutomu Tamada, Koji Shikimachi, Yu Iwatani, Fusao Saito, Yusuke Ishii: The State of the Art of the Development of SMES for Bridging Instantaneous Voltage Dips in Japan, Cryogenics, Volume 52, Issue 12, pp. 708-712, 2012.

89 S. Lee, K.P. Yi, S.H. Park, J.K. Lee, WS Kim, C. Park, J.H. Bae, K.C. Seong, I. Park, 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.

90 J. Li, M. Zhang, Q. Yang, Z. Zhang, and W. Yuan: SMES/Battery Hybrid Energy Storage System for Electric Buses, IEEE Transactions on Applied Superconductivity, 26 (4), 7403905, DOI: 10.1109/TASC.2016.2527730, 2016.

91 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, pp. 175-185, DOI: 10.1016/j.energy.2015.03.132, 2015.

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 H_2 supply network might be those where the LIQHYSMES plant can be combined with the production, storage, and distribution of H_2.

SET-Plan Targets

The SET-Plan targets taken for the material development roadmap are given in table 11. Due to the rapid development of 2 G 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 11: Targets for SMES materials towards 2030 and beyond[92].

Current performance	Target 2020-2030	Target 2050
Highly efficient >95% For short duration storage (electricity stored in magnetic field) Superconducting coil cooled below its critical T°	Increasing critical T° of the superconductors Second HTS generation: >current density at high magnetic field (i.e. >10m; >50 A) Enhance performances at high magnetic fields and reduce the cost of YBCO coated conductors	Cost reduction >5-10% ca. 100 €/kW (200€/kWh)

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

Current performance	Target 2020-2030	Target 2050
Highly efficient >95% For short duration storage (electricity stored in magnetic field) Superconducting coil cooled below its critical T°	Enhance performance and decrease cost of MgB_2 and 2 G wires and tapes by a factor of five Standardise SMES technology (cryostat, current leads, cooling) Improve the multi-physics designing tools Improve electronic control and coil protection Demonstrate HTS SMES in hybrid or stand-alone applications	Enhance performance and decrease cost of MgB_2 and 2 G wires and tapes by a factor of ten Reduce cost and loss of SMES technology (cryostat, current leads, cooling) by a factor of two Apply SMES in commercial applications

92 Commission Staff Working Paper: Materials Roadmap Enabling Low Carbon Energy Technologies, 2011. http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

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.

Hybridation 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 120-30 K with cooling power in the range of 100's of W, able to work with cryogens at 120 K or 77 K 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[93]. The world's first utility-scale CAES plant was installed and commissioned to operation by Asea Brown Boveri (ABB) at Huntorf, Germany, in 1978[94]. It has a rated power generation of 290 MW, or a full power output of just less than 3 hours[95]. 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[96]. 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 tertiary frequency control (spinning reserves)[97]. The common feature of these two CAES plants is that they all involve burning a fossil fuel – natural gas – in their electricity generation process.

93 B. J. Davidson, et al.: Large-Scale Electrical Energy Storage, Physical Science, Measurement and Instrumentation, Management and Education Reviews, IEE Proceedings A, vol. 127, no. 6, pp. 345–385, 1980.
94 Ibidem.
95 S. Succar, R.H. Williams: Compressed Air Energy Storage: Theory, Resources, and Applications for Wind Power, Technical Report, Energy Systems Analysis Group, Princeton Environmental Institute, Princeton University, 2008.
96 Ibidem.
97 S. Succar, R.H. Williams: Compressed Air Energy Storage: Theory, Resources, and Applications for Wind Power, H. Chen, T. N. Cong, W. Yang, C. Tan, Y. Li, and Y. Ding: Progress In Electrical Energy Storage Systems: A Critical Review, Progress in Natural Science, vol. 19, no. 3, pp. 291–312, 2009.

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[98].

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[99]. 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[100].

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.

Table 13: Application potentials of CAES related technology[101] .

Application area	Characteristics ([18, 50, 61 ~ 65])	Suitable or potential CAES related technology
Power quality	<1 MW, response time (milliseconds, <1/4 cycle), discharge duration (milliseconds to seconds)	Hybrid systems with small-scale CAES and battery or supercapacitor or other EES technologies with fast response
Energy management	Large-scale (>100 MW), medium/small-scale (<100 MW), response time (minutes), discharge duration (up to days)	Large-scale energy management (large-scale CAES); Small-scale energy management (small-scale CAES, LAES)
Renewable back-up power	100 kW-40 MW, response time (seconds to minutes), discharge duration (up to days)*	Multi-scale CAES, hybrid systems with CAES and capacitor or others with fast response may need, possible LAES

98 X. Luo, J. Wang; M. Dooner; J. Clarke and C. Krupke: Overview of Current Development in Compressed Air Energy Storage Technology, Energy Procedia, Vol. 62, pp. 603-611, 2014.
99 RWE Power, ADELE – Adiabatic Compressed-Air Energy Storage (CAES) for Electricity Supply, ADELE Brochure, 2016. https://www.rwe.com/web/cms/mediablob/en/391748/data/364260/1/rwe-power-ag/innovations/Brochure-ADELE.pdf
100 Lightsail Energy Ltd, 2016. http://www.lightsail.com
101 X. Luo, J. Wang: Overview of the Current Development on Compressed Air Energy Storage, EERA Report, 2016. 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.

Application area	Characteristics ([18, 50, 61 ~ 65])	Suitable or potential CAES related technology
Emergency back-up power	Up to 1 MW, response time (milliseconds to minutes), discharge duration (up to ~24 hours)*	Possible small-scale CAES, hybrid systems with small-scale CAES and other technologies with fast response
Time shifting	1 MW-100 MW and even more, response time (minutes), discharge duration (3-12 hours)	Multi-scale CAES and LAES
Peak shaving	100 kW-100 MW and even more, response time (minutes), discharge duration (hour level, <10hours)	Multi-scale CAES and LAES
Load levelling	up to several hundreds of MW, response time (minutes), discharge duration (up to ~ 12hours and even more)	Multi-scale CAES, possible LAES
Black Start	Up to rated output (depending on stored energy) response time minutes	Multi- scale CAES
Inertial Response	Provided in both compression and expansion	Multi- scale CAES
Frequency Response	MW range dependent on system operator response requirements	Multi- scale CAES
Reactive Power Response	MVar range dependent on system operator response requirements	Multi- scale CAES
Operating Reserve	XX MW – XX MW, range dependent on system operator response requirements	Multi- scale CAES

* Note that the limits can vary significantly depending on individual system operators' reserve response times and requirements.

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 14: The theoretical values of the maximum energy efficiency.

Efficiency	System Efficiency	Compression Efficiency	Heat storage Efficiency	Cold storage efficiency	Storage efficiency	Expansion Efficiency
Theoretical value	81.9%	91%	99%	99%	99.8%	92%

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

2016 - 2020	2020 – 2030
Achieving system efficiency of 60 – 65%	Achieving system efficiency around 70%

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 size/volume of the caverns should be maximised 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. Research should also be done to assess the subsurface stability of caverns if there is cyclic loading and unloading.
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. Also, research should investigate possibilities to combine CAES with other generation technologies to improve the business case.

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 highly 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[102] 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.

Liquid Air Energy Storage

Introduction

Liquid Air Energy Storage (LAES) 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, is not geologically limited, 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.

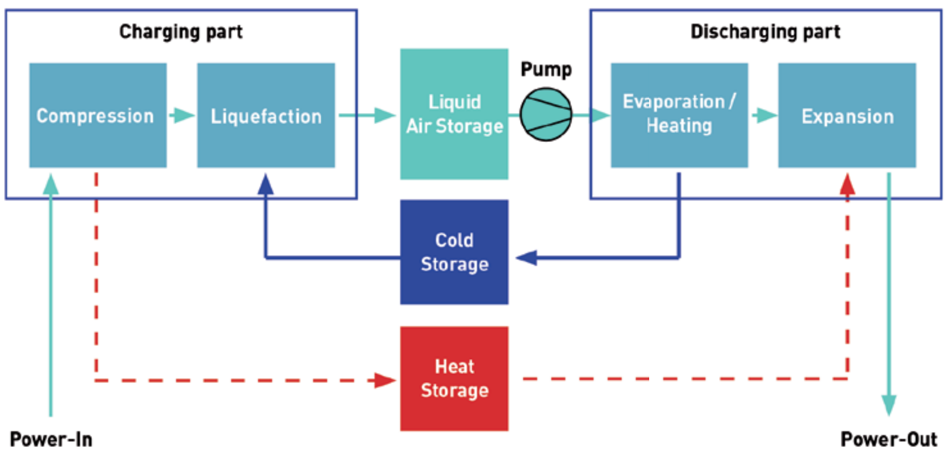


Figure 12: LAES mode of operation.

102 RWE Power, ADELE – Adiabatic Compressed-Air Energy Storage (CAES) for Electricity Supply, ADELE Brochure, 2010. https://www.rwe.com/web/cms/mediablob/en/391748/data/364260/1/rwe-power-ag/innovations/Brochure-ADELE.pdf

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[103]. 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 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[104]. 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. 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[105]. 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 2017. 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 large amounts of 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 as a 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

103 E.M. Smith, BSc, PhD, CEng, MIMechE: Storage of Electrical Energy Using Supercritical Liquid Air. Proceedings of the Institution of Mechanical Engineers, 191: 289-298, 1977.

104 K. Kishimoto, K. Hasegawa, T. Asano: Development of Generator of Liquid Air Storage Energy System, Mitsubishi Heavy Industries Ltd., Technical Review Vol. 35 No. 3, 117-20, 1998.

105 B. Stöver, A. Alekseev, C. Stiller: Liquid Air Energy Storage (LAES) - Development Status and Benchmarking with other Energy Storage Technologies, Power Gen Europe, Cologne, 2014. S. Wu, C. Bergins, B. Stöver, J. Naumovitz, C. Stiller, A. Alekseev, Liquid Air Energy Storage – A Flexible Solution for Grid Scale Applications, Power Gen Internationel, Orlando, 2014.

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, having a synchronous generator, LAES can provide physical inertia and power factor correction for dynamic voltage control.

- 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 15: SET-Plan targets.

Current performance	Target 2030	Target 2050
Pilot and pre-commercial demonstrators 5 MW storage (only power recovery unit deployed) Primary regulation capability Low cycle cost, high capital cost	Full commercial scale– 15 to 50 MW, 100s MWh Sub-second response capabilities (standalone, hybrid solution e.g. SMES) Increase regulation capacity in charging mode (liquefaction)	100 MW/GWh storage scale
Round trip efficiency (RTE) ~20% at pilot scale; 50-60% (predicted) for stand-alone commercial scale LAES; potential of >65% by utilisation of waste heat	Increase round trip efficiency up to 60-70% for standalone systems and much higher e.g. ~ 90%+ through harnessing of waste heat from thermal plants/industrial processes and waste cold from industrial processes and LNG terminals	RTE 70% for standalone systems through improving efficiency of liquefaction process, and novel thermodynamic cycles, and a higher ~100% through harnessing of both waste heat and waste cold from thermal plants/industrial processes and LNG terminals
250-600 €/kWh or 2000-3500€/kW (LAES size dependent)	Cost reduction: 150-400 €/kWh or 1000-2000 €/kW (LAES size dependent)	Mature LAES costs: <150€/kWh or < 1000 €/kW
Little attention paid to developing new materials and devices for enhanced performance of LAES	Advanced materials & devices for heat storage (from compressors and intermittent sources of waste heat) and cold storage for cold recycle; reduction of parasitic losses from compressors, cryogenic pumps and expanders	Optimal integration, operation, and management of LAES in low carbon grid environment

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.
- 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. Detailed integrated LAES-conventional plants design should be developed: in-depth integration studies and full-scale demonstrators of LAES with complementary plants, including coal, open cycle gas turbines, diesel generators, and liquefied natural gas regasification terminals, should prove LAES's potential and should inform the development of adequate business models.

2. Research in advanced materials, devices and systems specific to liquid air to reduce CAPEX and improve efficiency. This includes research into intense thermal energy storage (TES) materials, devices, and systems; maximising performance of cryogenic pumps and compressors for LAES; and exploratory research on advanced air purification units.

3. 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 CO_2, CH_4 and C_3H_8 should be investigated and demonstrated at pilot scale.

4. 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. In the short term, LAES applications in which waste cold or heat is harnessed should be considered for inclusion in energy efficiency programmes.

Depending on the scale of the demonstration and pilot test projects, the estimated budget for research funding could range as presented below:

Area	Funding requirement
Research in advanced materials	(€10s thousands – €100s thousands)
Devices and systems	(€100s thousands – €10s million)
Demonstrator at scales in the order or 10s of MW	(€10s million – €100s million)
Demonstrator at scales in the order or 100s of MW	(€100s million)

Similarly, adequate regulatory aspects and sound market conditions are necessary for the large-scale industrial uptake of LAES. In the short term, LAES applications in which waste cold or heat is harnessed should be considered for inclusion into energy efficiency programmes.

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.

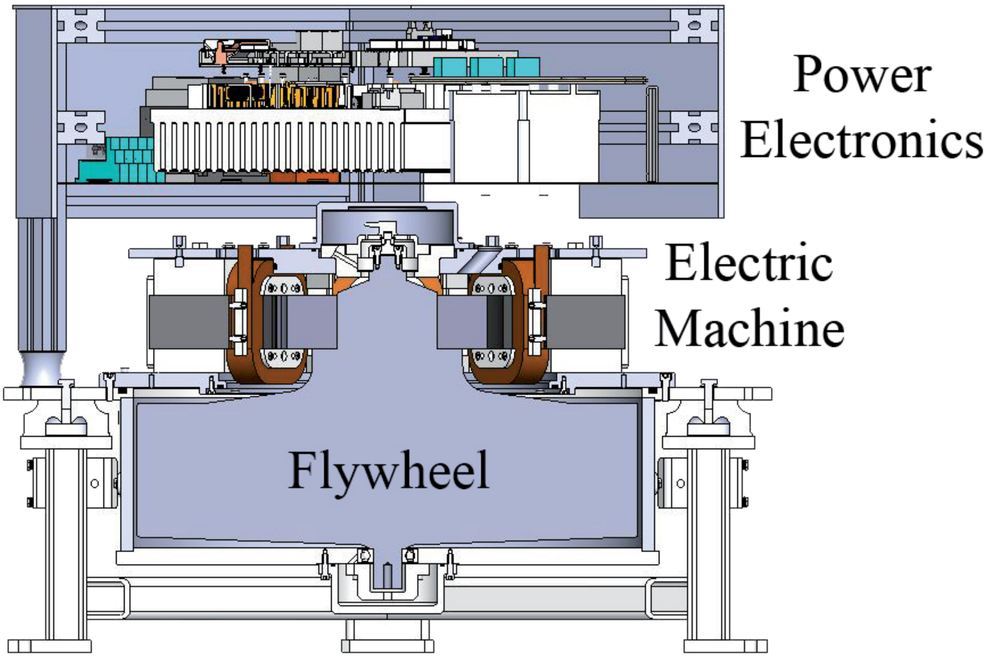


Figure 13: Basic scheme of a Flywheel. Source: CIEMAT.

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 manufacturing 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 energy 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 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 efficiency, reduce power consumption peaks, enable energy savings, and contribute to 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 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 16: SET-Plan targets.

Current performance	Target 2030	Target 2050
High cycle life: >100000 cycles Power: 100 – 1500 kW Energy: 0,5 – 50 kWh Roundtrip efficiency: 80-90%	Reduced friction, higher rotation speed for higher energy storage (>10 kWh) Stronger materials (composite) Large scale demonstration sites Development of competitive magnetic bearings	Higher energy storage density: >100 Wh/kg
Cost: 500-3000 €/kWh and 1000-2000 €/kW (depending on the power and energy levels)	Rotor manufacturing cost reduction <3000 €/kWh	Cost reduction: < 350 €/kWh

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 low witching 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[106].

106 George Roe: Boeing Flywheel Energy Storage Technology, 2012.

4. Digital control and communications/power electronics: digital control and fast communication improvements allow 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. Another important point is to increase the added value of the power electronics in the energy storage system, ensuring robustness and reliability and leading to a higher roundtrip efficiency.

5. Efficiency of the flywheels: reduction of losses in idle state.

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 this 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.

Pumped Hydro Storage

Introduction

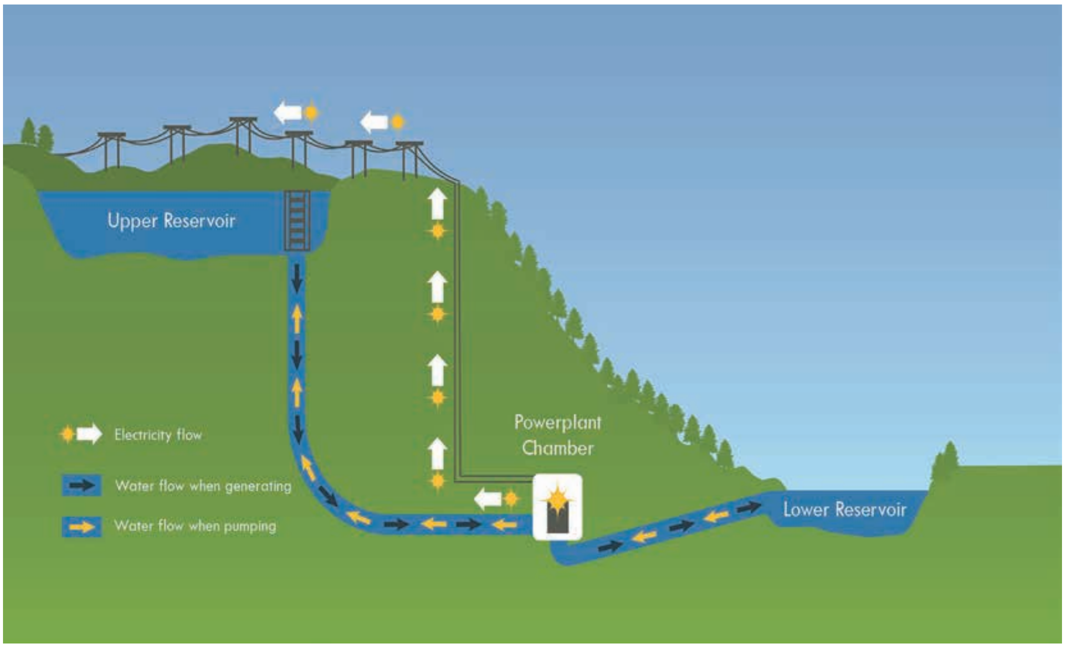


Figure 14: Principle of a Pumped Hydro Storage plant. Source: New Civil Engineer, 2016.

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 flexible[107]. This also increases both the flexibility and response time of PHS plants.

Not all hydro plants are PHS, however. Hydropower plants (HPP) utilise the potential energy of water being pulled by gravity through turbines to generate electrical energy. The principle is identical to the generating cycle of PHS, but there is no pumping capability present at a HPP. Thus, there is no possibility of storing electricity from the grid at a HPP. Still, the upper reservoirs that exist in connection to HPPs represent large volumes of stored potential energy that can be dispatched when needed. There are also many locations of reservoir hydro that have both an upper and lower reservoir available, perfect for retrofitting into PHS.

Due to the similarities between PHS and HPP, many of the research needs are the same for both technologies: introducing flexibility capabilities, e.g. by developing variable-speed generators; retrofitting existing HPP into PHS; enabling the development of small, non-conventional and multipurpose HPP; and expanding possibilities for installation of HPP.

Maturity of Technology

PHS is undoubtedly the most mature large-scale energy storage technology, representing the majority of installed energy storage capacity in Europe today. 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 in variable RES supply in North Western Europe using PHS[108].

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 16, below.

107 Electric Power Research Institute (EPRI): Quantifying the Value of Hydropower in the Electric Grid: Final Report, Palo Alto, CA, 1023144, 2013.
108 eSTORAGE: Potential for Conversion of Classical PSP to Variable Speed Units in EU15, Norway and Switzerland, 2016. http://www.estorage-project.eu/wp-content/uploads/2013/06/EXTRACT-of-eStorage-D4.1-Potential-for-conversion-of-classical-PSP-to-variable-speed-units.pdf

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

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

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[109]. 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[110].

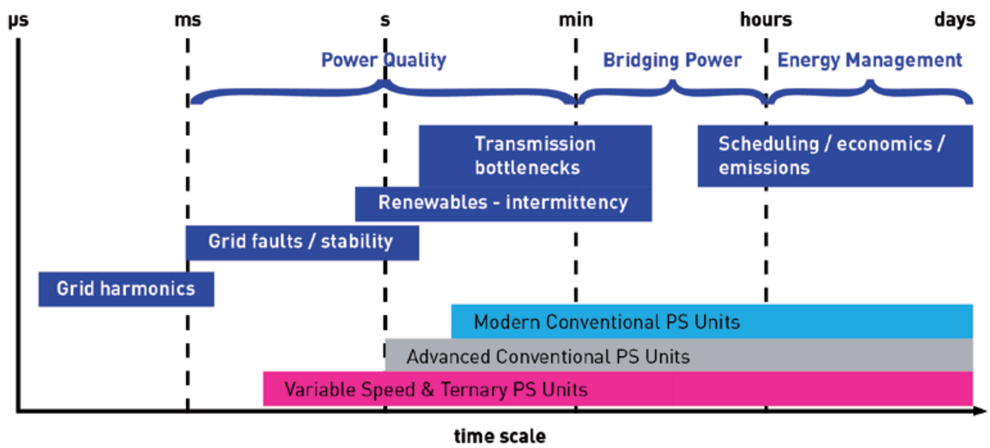


Figure 15: Timeframes for modern advanced PHS unit regulation[111].

109 eSTORAGE: Potential for Conversion of Classical PSP to Variable Speed Units in EU15, Norway and Switzerland, 2016. http://www.estorage-project.eu/wp-content/uploads/2013/06/EXTRACT-of-eStorage-D4.1-Potential-for-conversion-of-classical-PSP-to-variable-speed-units.pdf

110 L. Lenhard, A. Neto, O. Teller, H. van de Vegte: Developing Cost-Effective, Flexible, Reliable GWh-scale Energy Storage – An eStorage Project Update, 2015. http://www.estorage-project.eu/wp-content/uploads/2013/06/Hydro2015_Alstom_DNVGL_eStorage-Projects-Results-to-date.pdf

111 Electric Power Research Institute (EPRI): Quantifying the Value of Hydropower in the Electric Grid: Final Report, Palo Alto, CA, 1023144, 2013.

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.

  Requested response time: within10 minutes.

  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.

Current performance	Target 2020-2030	Target 2050
GW storage	Materials radical redesign & research on power electronic components	Efficiency improvement
Low cycle cost high capital cost		Cost reduction
\$500/kW to \$2000/kW (350 to 1500€/kW)	Turbine efficiency improvement	Expand possibilities of PHS installations
Round trip efficiency 70-80%	Increase regulation capacity in pumping mode	Ultrafast regulation
Primary regulation capacity		
	Increase pump-turbine stability in pumping mode	
	New concepts for underground PHS	Studies for first implementation of new underground PHS

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 for PHS

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 PHS applications as well as hybrid PHS-wind/photovoltaic applications for centralised/decentralised solutions should be supported.

As indicated above, research priorities for conventional hydro are largely similar to those of PHS.

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.

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

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 storage (SHS) raises or lowers 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.

		Sensible	Latent	TCS
Improve District Heating & Cooling performances	Shift heating and cooling productions	+		
	Maximise base load production	+		
	Reduce peak load production	+		
	Improve heat recovery from waste and from "already available excess heat"	+		
	Improve the heat/power balancing of heat & power cogeneration	+		
	Shifting power to heat	+		
Use and Integration of Low Carbon Energy for Heat Generation	Demand-driven/stabilising heat supply from local and district heating	+	0	0
	Demand-driven/stabilising heat supply from solar process heat	+	+	+
	Demand-driven/stabilising heat deployment from solar thermal power plants	+	+	0
	Decarbonisation of the residential heating sector using intermittent renewable energy (e.g wind, solar PV)	+	+	0
	Utilisation of Power-to-Heat concepts	+	+	0
	Combined solar systems	+	0	0
Increasing Energy Efficiency in Industrial Processes	Use of industrial waste heat	+	+	+
	Decoupling of power, heat and cold generation in cogeneration plants	+	+	0
Increasing Energy Efficiency in Buildings	Balancing heat and cold demand	+	+	+
	Decoupling of power, heat and cold generation in micro-cogen plants	+	+	0
	Balancing daily demand	+	+	+
	Balancing seasonal demand	+	0	+

* 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 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 (BTES), pit TES (PTES), and cavern TES, as well as hybrid versions (combined PTES and BTES), which have been piloted and are under development[112]. Steam-based storage solutions are also promising: some commercial CSP plants implement high pressure steam storage systems, which are useful for a short storage time.

Figure 16: Aerial view of Crescent Dunes molten salt storage. Source: COBRA.

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[113].

112 Nordell, B., Snijders, A., & Stiles, L.: The Use of Aquifers as Thermal Energy Storage (TES) Systems, in L. F. Cabeza, Advances in Thermal Energy Storage Systems, 2015.

113 National Renewable Energy Laboratory – Concentrating Solar Power Projects, 2016. https://www.nrel.gov/csp/solarpaces/

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.

Table 21: Characteristics of low/high temperature sensible energy storage technologies[114,115].

	UTES	LT-storage in liquids	HT-storage in liquids	HT-storage in solids
Energy density at typical ΔT in kWh/m³	15 - 80	60 - 100	75 – 200	75 – 150
Feasible size	Up to 15 GWh	Up to 1000 MWh	350 – 4000 MWh	1000 MWh
Cost of storage unit per kWh	0.1 – 10 €	0.4 – 10 €	20 – 70 €	15-40 €

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 reached high TRL levels for this application (TRL 9) and have become the standard solution for dispatching solar thermal electricity at full power. However, in other industrial applications their potential has not been completely explored (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. SET is used on location-independent storage systems for isentropic Power-to-Heat-to-Power (P2H2P) energy storage[116]. Promising solutions are based on right- and left-handed thermodynamic cycles with heat and cold sensible energy storage. This solution reaches TRL 6.

114 German Energy Storage Association e.V., Technology Factsheets, 2016. http://www.bves.de/technologien-2/#toggle-id-6
115 National Renewable Energy Laboratory, Solana Generating Station, 2015. https://www.nrel.gov/csp/solarpaces/project_detail.cfm/projectID=23
116 http://www.isentropic.co.uk/energy-storage

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-building storage systems: low-temperature solar heat of up to 40m3 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 dispatchable electricity. An example among many is the Solana power plant with 280 MWe and a storage system able to supply full power for 6 hours. CSP can also generate heat for district heating solutions.
- Power-to-Heat: molten salt storages offer potential for conversion of electrical energy to thermal energy or for use in district heating systems. 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. Waste heat in district heating can benefit greatly from the use of storage, increasing the amount of heat recovery.
- Steam accumulators enable balancing the steam load between steam sources and consumers, thereby saving large amounts of energy.
- 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 22.

Table 22: SET-Plan target for thermal energy storage.

Target description	Year
Significantly reduced heat losses and increased energy efficiency	n/a
Efficient charging and discharging characteristics	n/a
High flexibility for building integration	n/a
Reduction of mass-produced containment costs by 20%	n/a
Containment of 1000L tank (excl. insulation and VAT) of 300 – 700€	2020
Development of innovative modular concepts	n/a
Durability and lifetime predictions in the high-temperature sector (e.g. corrosion, thermomechanical issues)	n/a
Development of new, improved sensible energy storage materials to increase the heat capacity, thermal conductivity or other relevant properties for the storage and heat transport by means of basic material science research	n/a
Drastic cost reduction by means of the use of cost-effective storage materials and concepts	n/a

Other targets relevant to sensible heat storage include:

Table 23: SET-Plan for heat storage.

Target description	Year
Development of liquid storage media to enlarge maximum operating temperature up to 700°C (while maintaining a freezing point below 250°C) up to TRL 6-7.	n/a
Reduction of the minimum operation temperature of salts to avoid large tracing energy needs.	n/a
Development of thermocline-filler molten salt storage system with reduced CAPEX of 25% up to TRL 7-8	2020
Development of alternative molten salt tank designs with reduced CAPEX up to TRL 7-8	n/a
75% energy efficiency of UTES	2020
Cost of high-performance insulation reduced below 100 €/m^3	n/a
Develop innovative fluids such as gaseous heat transfer fluids (air, super-critical CO_2 etc.)	n/a

Gaps in Research

Research should be conducted on the adaptation of TES technology for its use both in power plant and industrial process heat applications. Additionally, 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. Finally, 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. 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. Research on novel high-temperature TES concepts for cost reduction or improved operation in system, particularly of a large storage capacity (e.g. thermocline/filler of molten salt storage, solid particle concepts). Also, 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).
2. 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.
3. 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 CO_2, etc…). Long-term reliability of the material is a crucial aspect.
4. 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). There is also a need for optimised control of UTES to improve energy savings and reduce the use of back-up systems.
5. 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[117]. Additionally, costs can be reduced through thermocline approaches for molten salt storage systems in combination with solid filler materials. Funding for TES applied to district heating could lead to significant efficiency and environmental improvements, while supporting RES integration.

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.

One 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[118]. Depending on the working pressure, storage materials with a phase change 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[119]. However, metals and carbonates have also revealed an attractive potential in this temperature range and higher.

117 European Parliament, Resolution of 13 September 2016 on an EU Strategy on Heating and Cooling. http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+TA+P8-TA-2016-0334+0+DOC+XML+V0//EN

118 The difficulties coming from the needed pressure, however, make this technology difficult to implement. Other alternatives can also be used such as ionic liquids or gases, if an appropriate heat transfer is provided.

119 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.

Since PCM materials transition between solid and liquid phases and the materials themselves have very poor thermal conductivities, heat transfer enhancement mechanisms (such as extended fins, encapsulation, composites, heat pipes, etc.) need to be incorporated in the heat exchanger to improve thermal conduction. Other options considered for high temperatures besides nitrate salts include metals, liquid crystals, where liquid to liquid phase transitions take place.

The key characteristics of these various storage technologies are depicted in table 24.

Table 24: Characteristics of LHS technologies[120].

	LT latent heat storage	HT latent heat storage
Latent heat energy density of storage unit in kWh/m^3	80 - 110	90 - 100
Feasible size	10 kWh – 2.5 MWh	10 kWh – 10 MWh
Cost of storage unit per kWh	0.4 – 10 €	20 – 70 €

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 has 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-capacity storages are TRL 5-8.

Figure 17: Latent storage system with 700 kW power, 1h storage capacity, Source: DLR.

120 German Energy Storage Association e.V., Technology Factsheets, 2016.http://www.bves.de/technologien-2/#toggle-id-6

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[121] 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 interacts 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 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 could 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. However, this solution would first have to be demonstrated with SHS.

121 National Academy of Science and Engineering (acatech), Energy Storage: Technology Factsheets for Analysis of "Flexibility Concepts for Power Generation in 2050", 2015. http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Publikationen/Materialien/ESYS_Technologiesteckbrief_Energiespeicher.pdf

SET-Plan Targets

Table 25: SET-Plan targets.

Target description	Year
Improved materials and systems for TES with PCM in buildings	
Specific investment cost of latent heat storage reduced below 50 €/kW	2020
Increased storage density and thermal transport properties for PCM systems	
Novel PCM development with adjustable phase-change temperature	
Heat exchangers which also encapsulate the PCM	
Latent heat storage with stable and controllable discharging power	2020
Separation of power and capacity through active heat exchangers	
Power-to-Heat integration into latent heat storages	

Gaps in Research

Today no LHS with stable and controllable discharging power is available. Due to technical simplicity, almost all LHS today contains 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.

Materials for use as PCM are still expensive and not always reliable. There is a long way to go before the PCM molecules tested in laboratory can be used in large volumes and to improve the stability of the molecules over time. Therefore, 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. This is very important since most of the proposed PCMs present poor heat transport properties (thermal conductivity).

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. 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. These efforts would have to be complemented with the development and demonstration of improved methods to determine the state of charge of LHS. This is crucial for controlling thermal systems coupled to LHS in an optimal way in order to deliver services in the electrical and/or thermal grid. State of charge determination of LHS is complex and there is a need for low cost systems.

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 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.
4. 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. Improvement of the mechanical properties is also an important step so the material may maintain its performance over 1000s of cycles.
5. 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 deep research into PCMs. Further development of PCM systems at ~400°–500°C without the use of expensive materials such as lithium salts and development of cold storage PCMs for applications at ~7-12 °C with very low super cooling.

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 and low cost systems to determine the state of charge of LHS.

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 26.

Table 26: Characteristics of TCS technologies[122].

	Chemical Reactions	Sorption Processes
Energy density of reaction or sorption in kWh/m^3	100 - 400	120 – 250 kWh/m^3
Feasible size	System-dependent	2 – 4 MWh
Cost of storage unit per kWh	Target: 10 – 90 €/ kWh	10 - 130 €

122 National Academy of Science and Engineering (acatech), Energy Storage: Technology Factsheets for Analysis of "Flexibility Concepts for Power Generation in 2050", 2015. http://www.acatech.de/fileadmin/user_upload/Baumstruktur_nach_Website/Acatech/root/de/Publikationen/Materialien/ESYS_Technologiesteckbrief_Energiespeicher.pdf

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.

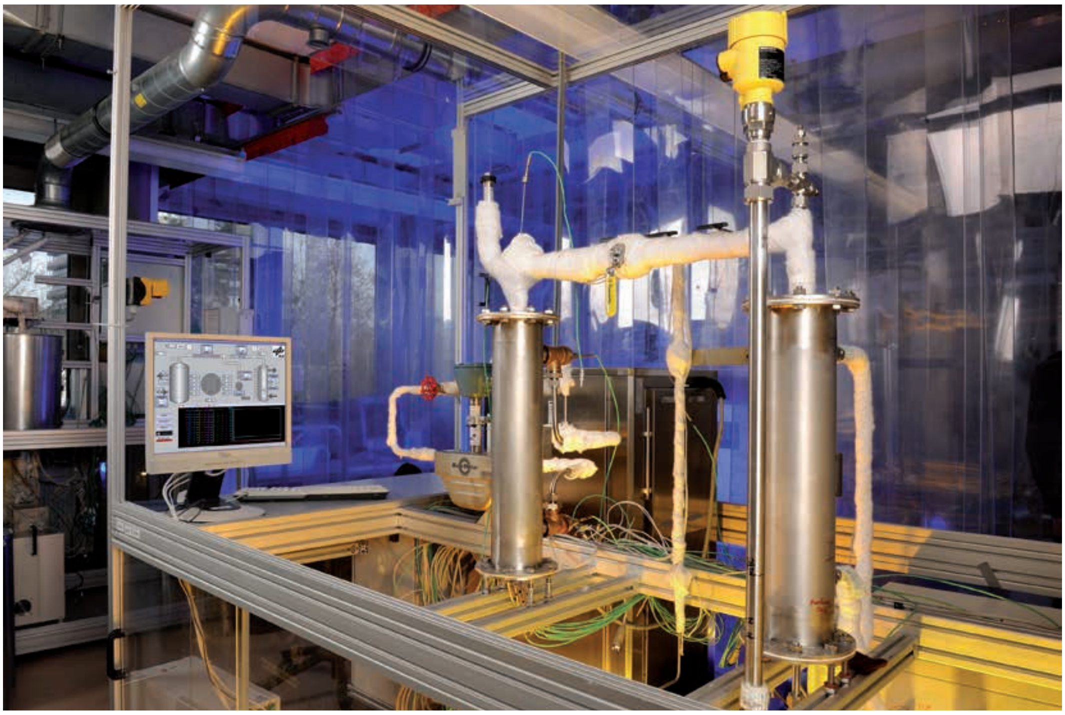


Figure 18: Test stand for thermal upgrade of waste heat at T>140°C. Source: DLR.

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 27: SET-Plan targets.

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

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:

    - Development of adjustable and simplified reactor concepts;

    - Improved integration of gaseous reactants;

    - Selection and advancement of the storage material–thermodynamics, kinetics, cycling stability;

    - 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 three 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.

CHAPTER 7

MARKET DESIGN AND POLICY RECOMMENDATIONS

7 MARKET DESIGN AND POLICY RECOMMENDATIONS

The deployment and system integration of energy storage technologies in Europe depends to a large extent on the strength of R&D efforts. However, 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, the demonstration of first-of-a-kind real-scale technologies faces regulatory barriers. Also, 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 and system integration 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 electricity123, as well as the proposed directive on common rules for the internal market in electricity124, 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

Remove regulatory barriers to demonstration projects.

In addition to support for technical innovation and demonstration, there is a very important role for demonstration of the practicability and commercial viability of storage projects in a number of applications. Demonstration projects allow for gathering valuable knowledge about the market applications and commercial arrangements for energy storage systems. These projects will in many cases be founded on multiple revenue streams, multiple clients, and multiple contracts. There is complexity in the interface between these, which involves regulatory and commercial risk.

The regulatory framework must allow for:

a) funding of such demonstration projects through appropriate revenue collection;

b) the careful and limited waiving of particular regulatory safeguards (such as a network operator not being able to own storage);

c) the prudent waiving of technical and commercial requirements for network connection, especially in jurisdictions where the use of energy storage is not commonplace; and

123 European Commission: Regulation on the Internal Market For Electricity, 2016. http://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v9.pdf

124 European Commission: Directive on Common Rules for the Internal Market in Electricity, 2016. http://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v7_864.pdf

d) appropriate participation by such facilities in relevant energy or service markets.

Such demonstration projects are a very effective route to pull technologies into commercialisation; it is not sufficient just to fund a new technology to see if it works.

Recommendation 2

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 allow cross-sectorial interfaces, e.g. electricity "in" and heat, gas or fuel "out", to be considered as energy storage, as this enables 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 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."[125]

However, EASE proposes propose 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 linking energy storage to 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. This change would also enable a definition of the role and accounting rules of Guarantees of Origin of renewable electricity that has been stored. Other specific, context related clarifications could emerge to resolve precise points, where needed.

125 European Commission: Directive on Common Rules for the Internal Market in Electricity, 2016.http://ec.europa.eu/energy/sites/ener/files/documents/1_en_act_part1_v7_864.pdf

Recommendation 3

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 or installing FACTS devices), 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. With this purpose and in line with recommendation 1, regulated entities shall be allowed to own, manage and operate energy storage also in case of deployment of innovative projects aimed at promoting the development of new technologies or market mechanisms.

- 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.

Recommendation 4

Eliminate unwarranted/double charging in a coordinated approach at European level. Whether and to what extent storage should finally contribute to grid costs merits a dedicated debate at European level.

Energy storage is not a load or a generator; it is storing energy for later use in the grid (e.g. providing transmission or distribution services, peak capacity or other ancillary services). Energy storage usually alleviates the grid and is a complement to grid development. It follows that storage should be exempted from grid charges, or only have a relatively small contribution.

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 generated and consumed once, are reflected in the legal framework, meaning a kWh cannot be taxed twice as a generator or a consumer.

Recommendation 5

Ensure the procurement of all energy and ancillary services is market-based, subject to a Cost-Benefit Analysis (CBA).

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[126]. 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 6

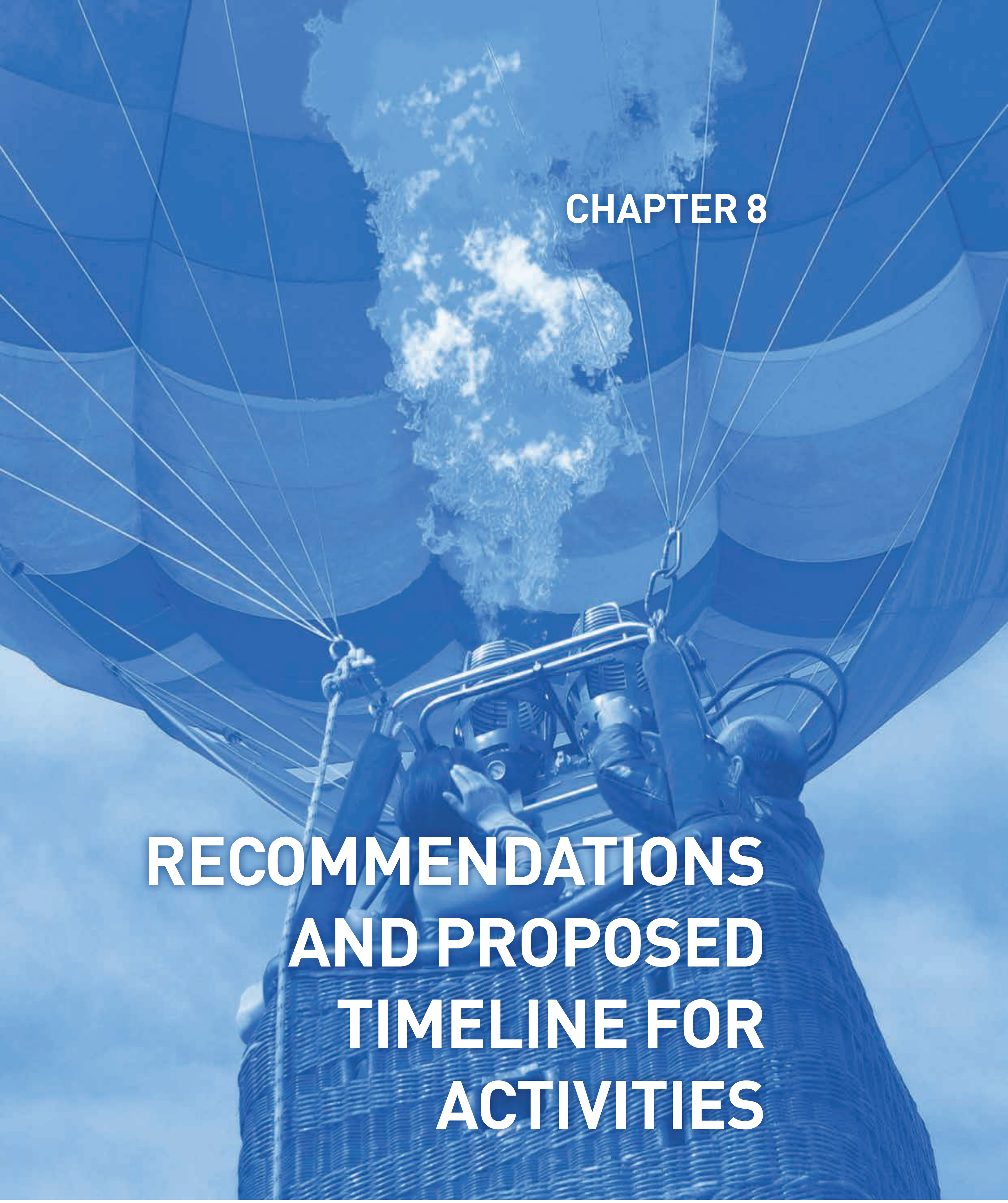
Establish energy storage as a separate asset class.

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[127]. 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 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. Even more than just supporting these technologies, a suitable regulatory framework can allow energy storage to live up to its full potential for supporting the integration of RES while ensuring power system efficiency.

126 RSE: Battery Energy Storage System Applications for the Provision of Dispatching Services: Cost-Benefit Analyses, presentation by Silvia Canavese at PowerGen Europe Conference, 2016.
127 European Parliament Report: Towards a New Energy Market Design (2015/2322(INI)), 2016. http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+REPORT+A8-2016-0214+0+DOC+XML+V0//EN



CHAPTER 8

RECOMMENDATIONS AND PROPOSED TIMELINE FOR ACTIVITIES

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 its impact depends on further technological developments and cost reductions for storage. An effective and coordinated RD&D effort in Europe can support the growing 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 RD&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 the storage technology: 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. Lastly, the promising area of hybrid energy storage systems, combining two or more technologies, merits increased attention in RD&D programmes.

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 the regulatory framework. 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, including particularly large-scale energy storage systems. These programmes will be necessary to support the deployment of the technologies needed within a short timeframe. Pilot programmes would be particularly valuable for chemical storage, grid-scale battery storage, LAES, new advancements of PHS technology in terms of flexibility or development potential, and intermediate heat storage for adiabatic CAES. Projects should also include studying the benefits and technical feasibility of hybrid energy storage systems. Demonstration projects should address key issues such as software development to improve modelling and efficient management of energy storage systems, as well as how to aggregate different applications. These demonstration projects will, over the next 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 and hybrid systems.

- 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 for short-, medium-, and long-duration services 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.

- 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 the 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 costs. 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 supercapacitors.

- Designate energy storage as an Important Project of Common European Interest (IPCEI)[128]. 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 technology, 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.

128 See European Commission: State Aid: Commission Adopts New Rules to Support Important Projects of Common European Interest, 2014. http://europa.eu/rapid/press-release_IP-14-673_en.htm

- 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 to define and promote ways to successfully scale up technologies within the EU.

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.

Within the next 2-5 years:

- 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.

- 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.

- 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. Assess the relative merits of services from stationary vs mobile (aggregated EV) storage facilities, and identify opportunities for mutual learning.

- 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 system services and load shifting.

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 next 10-20 years.

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ABBREVIATIONS AND ACRONYMS

A-CAES	Adiabatic Compressed Air Energy Storage
AA-CAES	Advanced Adiabatic Compressed Air Energy Storage
AC/DC	Alternating Current/Direct Current
Al	Aluminum
ARPA-E	Advanced Research Projects Agency - Energy
BEV	Battery Electric Vehicle
BTES	Borehole TES
C	Celsius
CAES	Compressed Air Energy Storage
CBA	Cost-Benefit Analysis
CH_4	Methane
C_3H_8	Propane - C_3H_8
CH_3OH	Methanol
CO_2	Carbon Dioxide
COP21	Conference of the Parties
CSP	Concentrated Solar Power
D-CAES	Diabatic Compressed Air Energy Storage
DSO	Distribution System Operator
DME	Dimethyl Ether
EASE	European Association for Storage of Energy
ECs	Electrochemical Capacitors
EERA	European Energy Research Alliance
EERA JP ES	EERA's Joint Programme Energy Storage
EMIRI	Energy Materials Industrial Research Initiative
ES	Energy Storage
ESS	Energy Storage Systems
EU	European Union
EUROBAT	Association of European Automotive and Industrial Battery Manufacturers

EV	Electric Vehicles
FCR/FRR	Primary Frequency Control
FRRa	Secondary Frequency Control
FRRm	Tertiary Frequency Control
GW	Gigawatt
GWh	Gigawatt Hours
GWhth	Gigawatts Hours Thermal
H_2	Hydrogen
H_2O	Water
HaE	Heat and Electricity Storage
HBr	Hydrogen Bromine
HEV	Hybrid Electric Vehicles
HTF	Heat Transfer Fluid
HTS	High-Temperature Superconductors
HPP	Hydropower Plants
HVDC	High Voltage Direct Current
ICT	Information and Communication Technology
IPCEI	Important Project of Common European Interest
I-CAES	Isothermal CAES
IEA	International Energy Agency
IEA TCP	IEA Technology Collaboration Programme
KIT	Karlsruhe Institute of Technology
K	Kelvin
kV	Kilovolt
kWh	Kilowatt Hour
LIQHYSMES	Liquefied Hydrogen with Superconducting Magnetic Energy Storage
LAES	Liquid Air Energy Storage
LCAP	Lithium-ion Capacitor
LCOE	Levelised Cost of Energy
LCOSE	Levelised Cost of Stored Energy
LCH_4	Liquid Methane
LH_2	Liquid Hydrogen
LHS	Latent Heat Storage
LN_2	Liquid Nitrogen

Li-ion	Lithium-ion
Li-S	Lithium–sulphur
LSU	LIQHYSMES Storage Unit
LTS	Low Temperature Superconductors
m	Meter
Mg	Magnesium
MgB_2	Magnesium Diboride
Mg-S	Magnesium-sulphur
MJ	Megajoule
MVar	Megavolt Ampere Reactive
MW	Megawatt
MWe	Megawatt Electric
$NaNiCl_2$	Sodium-Nickel Chloride
NaS	Sodium-Sulphur
NiCd	Nickel–Cadmium
NH_3	Ammonia
Ni-MH	Nickel–Metal Hydride Battery
O_2	Oxygen
OME	Oxy-Methylene Ether
P2G	Power-to-Gas
P2H2P	Power-to-Heat-to-Power
P2X	Power-to-X
PCM	Phase-Change Material
PEM	Proton Exchange Membrane
PHEV	Plug-in Hybrid Electric Vehicles
PHS	Pumped Hydro Storage
PTES	Pit TES
PV	Photovoltaic
R&D	Research and Development
RD&D	Research, Development and Demonstration
R&I	Research and Innovation
RES	Renewable Energy Sources
RFB	Redox Flow Batteries
rpm	Revolutions Per Minute

RPT	Reversible Pump Turbine
RTE	Round Trip Efficiency
SETs	Smart Electric Thermal Storage Heaters
SET-Plan	European Strategic Energy Technology Plan
SHS	Sensible Heat Storage
SMES	Superconducting Magnetic Energy Storage
TCS	Thermochemical Storage
TCM	Thermochemical Materials
TES	Thermal Energy Storage
TRL	Technology Readiness Level
TS	Ternary Set
TSO	Transmission System Operator
TWh	Terawatt Hours
UPS	Uninterruptable Power Supply
UTES	Underground Thermal Energy Storage
V2G	Vehicle to Grid
Va	Vanadium
VS	Variable-Speed
Zn	Zinc
ZnBr	Zinc-Bromine

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