

Joint EASE/EERA recommendations for a

EUROPEAN ENERGY STORAGE TECHNOLOGY DEVELOPMENT ROADMAP TOWARDS 2030



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. EASE actively supports the deployment of energy storage as an indispensable instrument to improve the flexibility of and deliver services to the energy system with respect to European energy and climate policy. EASE seeks to build a European platform for sharing and disseminating energy storage-related information. EASE ultimately aims to support the transition towards a sustainable, flexible and stable energy system in Europe.



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 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.

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CHAPTER 1

SUMMARY

1 SUMMARY

The present roadmap and recommendations aim to describe the future European needs for energy storage in the period towards 2020-2030. It also gives recommendations on which development will be required to meet the needs. The storage applications in focus are mainly those directly related to an electricity system with significantly increased share of renewable generation, whereas needs for energy storage related to the future fuelling of transportation are only marginally mentioned.

The roadmap is the result of a joint effort between the European Association for Storage of Energy and the Joint Programme on Energy Storage under the European Energy Research Alliance. The central parts of the work were done in January-February 2013 by a core working group composed of members appointed by both organisations.

As a part of the work on the document the first draft was presented at a workshop early February 2013, where prominent European parties interested in energy storage were invited and encouraged to give comments and suggestions on how to improve the roadmap. The workshop was attended by more than 30 delegates and reflected a widespread interest in the topic of energy storage. Many valuable inputs were received by the working group after the workshop and more comments were received after the second draft of the roadmap was made available first of March.

The basic assumption that energy storage will be required in the sustainable energy system of Europe is supported widely in numerous reports describing possible future scenarios of the European landscape. The assumption is furthermore supported by quantitative modelling work assessing the generation profile of a complete renewable European society. The quantitative analyses unambiguously point out a 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 renewables, electricity transmission capacity across Europe, penetration of demand side management and alternative back-up power availability (e.g. biomass or acceptance of limited use of fossils in short time intervals).

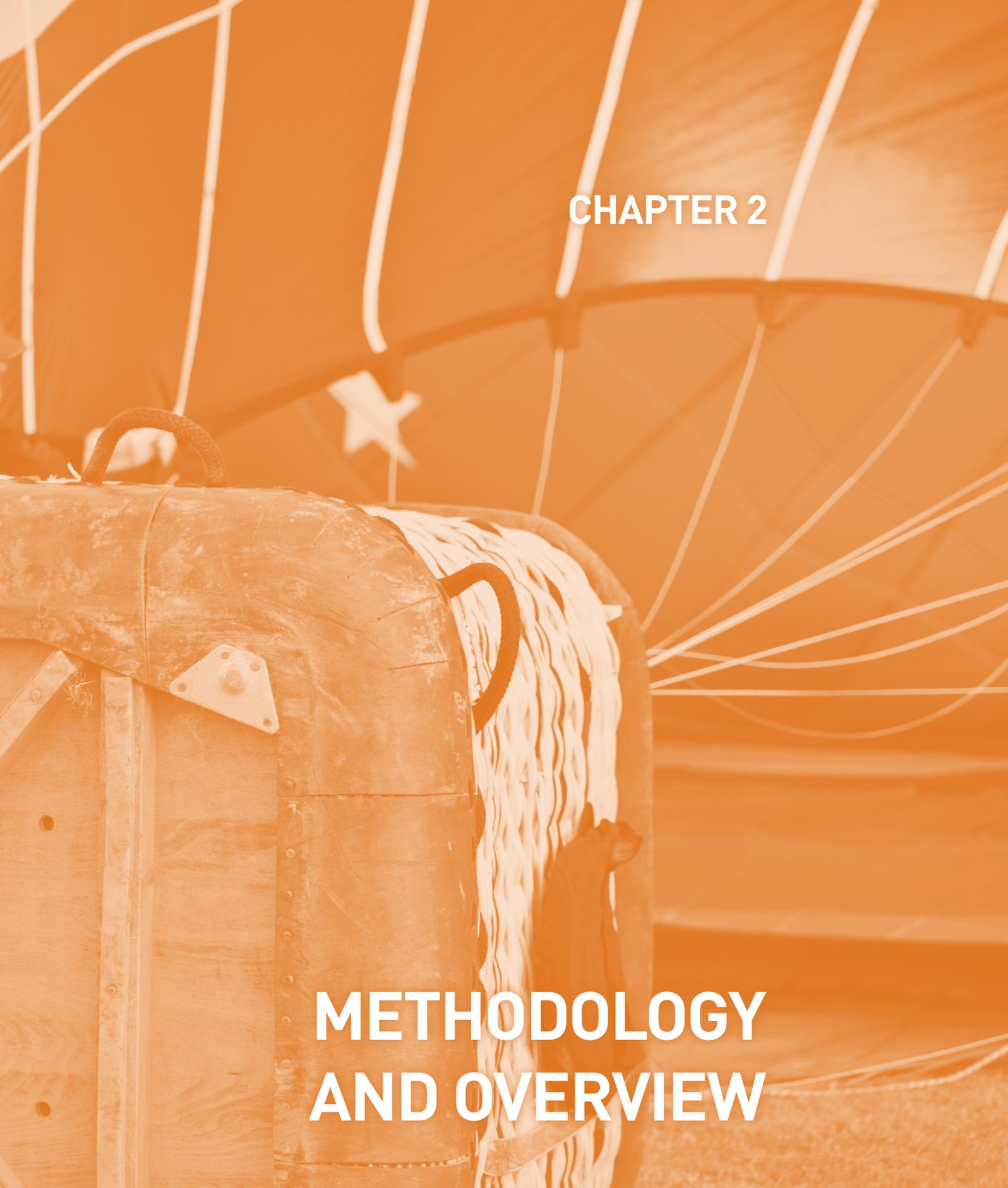
Based on this assumption we have aimed to encircle those energy storage technologies, which members of EERA Joint Programme ES and EASE believe hold the largest potential for economic and technical development allowing them to be applied on market terms in the future 10 to 20 years. We are technology experts with industrial and research background and by joining forces we believe that we have activated the deepest insight in storage technologies available in Europe.

The roadmap describes the first and major application fields for energy storage necessary for the European electricity and energy systems. These storage assets are expected to be applied within generation, transmission and distribution of electricity as well as at the end consumers. The roadmap also describes the main future challenges for storage technologies and points out how we have identified the technologies we believe to be the most promising technologies for the next decades. The selected technologies are categorised in chemical, electrochemical, mechanical and thermal categories as well as a category for electromagnetic energy storage.

The roadmap contains a section devoted to “Market design and policy issues”. We believe these issues should be addressed jointly by authorities and system operators to secure the optimal introduction of storage technologies in the energy systems and maximum benefit for society. Storage systems are still to be fully integrated into the arsenal of regulatory tools available to system operators.

Finally the roadmap gives a set of recommendations and a proposed timeline for the required efforts in a broad outline over the next decades. For details the reader is referred to the specific technology sections.

It is important to note that the recommendations given in the present Roadmap should not preclude supplementary R&D interest and resources in other technologies that are not presently believed to hold a commercial potential in the 10-20 year period. Technical breakthroughs in other storage technologies may completely change the basis for the present recommendations.



CHAPTER 2

METHODOLOGY AND OVERVIEW

2 METHODOLOGY AND OVERVIEW

The basic assumption that energy storage will be required in the sustainable energy system of Europe is supported widely in numerous reports describing possible future scenarios of the European energy landscape. The assumption is furthermore supported by quantitative modelling work assessing the generation profile of a complete renewable European society based on technical, scientific data and reasoning. The quantitative analyses unambiguously point out a 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 renewables, electricity transmission capacity across Europe, penetration of demand side management and alternative back-up power availability (e.g. biomass or acceptance of limited use of fossils in short time intervals).

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When pointing out the most promising storage technologies we have paid due attention to the present state of European competences in industry and research 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 work of preparing the document has been done by a joint core working group with representatives from both organisations. From EERA the subprogram leaders have attended the working group and in EASE a dedicated task force was pointed out to take part in the working group. Finally all EASE and EERA members have had the opportunity to comment on the document and make suggestions for corrections. Thus the present document indeed reflects the opinions and viewpoints of all EASE and EERA members.

In addition, both EASE and EERA believe that ensuring a broad stakeholder participation in this roadmap is fundamental for its success.

Following the principles of transparency and openness, we invited a group of relevant stakeholders, which were identified together with the European Commission, to contribute to this joint EASE/EERA Roadmap.

The stakeholders had different possibilities to provide feedback along the process:

- EASE and EERA organised a stakeholders workshop to introduce the first draft of the roadmap and gathered the opinions of the participants;
- By sending written comments on the first draft;
- By sending written comments on the second draft.

The Roadmap document gives a short introduction to the topics of relevance as well as a short description of the mission and objectives of the Roadmap. Corresponding to the technological nature of this document, it is organised by the different technologies. Given the fact that the technology development will not be the only driver for market uptake each of these sections include potential applications as well as the most obvious market opportunities.

Finally the document gives recommendations and conclusions about timeline and efforts to make the required development become a reality. The recommendations address the European industry as well as the European research society and the European Commission. In addition to the comprehensive technology descriptions, a section of the Annexes is dedicated to reference other similar recent Road mapping efforts done by other organisations or countries. The results of those efforts are integrated in the present work.



CHAPTER 3

INTRODUCTION AND BACKGROUND

3 INTRODUCTION AND BACKGROUND

This Roadmap is aimed at decision-makers, stakeholders and technical experts.

Energy storage technologies are crucial for achieving the European climate energy objectives as defined in the European Union's (EU) "20-20-20" targets¹ and in the European Commission's (EC) Energy Roadmap 2050². However, in order to achieve the 2050 targets an intermediate step is required and that is the reason why both EASE and EERA adopted the 2030 as timeframe for this exercise.

This Roadmap outlines European Research, Development & Demonstration (RD&D) needs for energy storage in a given timeframe, defining major areas where actions are necessary to achieve the level of technological maturity for energy storage market uptake.

It also provides high-level recommendations on market design defining EU-wide minimum requirements to support the development of a business case for energy storage.

3.1 The future European energy landscape

European energy and climate strategy

In December 2008, the European Parliament and the European Council agreed upon the so-called Climate and Energy Package. It became law in June 2009. The legislative package put in place, collectively known as the "20-20-20" targets, is composed of two binding targets and a non-binding one on energy efficiency:

- A reduction in EU greenhouse gas emissions of at least 20% below 1990 levels by 2020;
- Increasing the share of renewable energy to 20% in EU's energy consumption by 2020;
- Improving the EU's energy efficiency by 20% by 2020 compared to business as usual.

The core of the package comprises complementary legislation which is of utmost importance for the power industry, from generation, transmission and distribution to consumption.

In December 2011, the EC published its Energy Roadmap 2050. In this context, it is important to point out that this Communication, although providing important analysis on long term views for the energy policy based on different energy mix assumptions, does not claim to define the future.

In all scenarios of the Roadmap, the share of renewable energy sources (RES) in gross final energy consumption will achieve at least 55% in 2050. Switching to RES will inevitably lead to a situation in which, from time to time, generation will largely exceed demand or vice versa, with specific concerns to transmission and distribution networks.

Energy storage is especially well suited to respond to this challenge and to ensure a continued security of energy supply at any time. This is why the EC Energy Roadmap 2050 recognises the vital role of energy storage technologies for a progressively decarbonised European energy system, as also clearly stated in DG ENER's Working Paper The future role and challenges of Energy Storage Energy³.

¹ http://ec.europa.eu/clima/policies/package/index_en.htm

² EC Energy Roadmap 2050

³ http://ec.europa.eu/energy/infrastructure/doc/energy-storage/2013/energy_storage.pdf

With binding targets for 2020 and political aims for 2050, policy and R&D goals for 2030 will help to ensure a degree of reliability, on the short, medium and long term, necessary for adequate investments in the energy sector.

Perspectives for energy demand and supply in Europe for 2030 and 2050

According to the IEA⁴, electricity will play a central role in the future energy system and its consumption is likely to double at global level in its 2 degree scenario (2DS).

To achieve the 2DS and a low-carbon economy massive deployment of low-or zero-carbon technologies is needed. In fact, this scenario foresees that the use of renewable energy sources (RES) grows rapidly and they generate more than half (57%) of global electricity, with solar and wind each providing around 15% in 2050.

The same picture is true also for the EU:

- Growth in EU electricity demand by 2050 is somewhat smaller than globally, but power production still increases by nearly 50% from today's levels.
- In the 2DS scenario, the European electricity mix is also largely decarbonised.
- Wind, solar and hydro all play an important role.
- Nuclear power will be an important part of the European energy mix.

The massive deployment of low-or zero-carbon technologies will require substantial investments in low-carbon technologies over the next four decades. European countries are the frontrunners when it comes to the deployment of RES, mainly driven by national support policies. EU countries accounted for 27% of the global wind capacity added in 2010, and for 17% of the solar one. France ranked among the Top 10 countries in new wind and solar PV capacity built in 2010 (rank 7 in each case). Nevertheless, in the 2DS, investment efforts in the EU have to be intensified over the next four decades for many RES, but also for nuclear and Carbon Capture and Storage (CCS) compared to the slow deployment over the last five years.

Conclusions from existing projections

The same report⁵ acknowledges that in the future decarbonised energy system all flexibility sources will be needed:

- "Dispatchable" power plants;
- Demand-side response via a smart grid;
- Energy storage;
- Interconnection with adjacent markets.

In the section below, a closer look on how energy storage can support decarbonisation goals is given.

⁴ "Energy Technology Perspectives 2012 – Pathways to a Clean Energy System", Report IEA (International Energy Agency), 2012.

⁵ "Energy Technology Perspectives 2012 – Pathways to a Clean Energy System", Report IEA (International Energy Agency), 2012.

3.2 How can energy storage support present political goals?

The growing penetration of RES, in particular non-dispatchable generation such as wind and photovoltaic (PV), will increase the need for flexibility in the energy system. Energy storage is – in combination with other measures – well suited to respond to this challenge and to ensure a continued security of energy supply at any time.

Energy storage will provide essential services along the whole energy value chain and will thereby support in numerous aspects the transition towards a secure, competitive and decarbonised energy system in Europe:

- **Balancing Demand & Supply:** The increasing variability at the generation side requires technologies and procedures for balancing energy demand and supply. By allowing a timely and geographical displacement between consumption and generation sites, energy storage promotes the integration of RES generation.
- **Managing Transmission & Distribution grids:** Studies⁶ confirm that even with perfect build out of transmission capacities storage will have to become an essential element of the future electricity infrastructure to stabilise the grid. Moreover, some storage technologies could be realised much faster than grid upgrades.

In a landscape of increasingly decentralised and fluctuating electricity production and consumption, storage can optimise the use of generation, transportation and distribution assets. Storage enables grids to be sized closer to average energy flows, instead of peak power requirements, thereby also reducing transmission losses. Storage can contribute to the stability and reliability of grids as it supports especially local grid management functions that increase the grid's hosting capacity of variable renewable generation.

- **Promoting demand side management:** Storage technologies will play a key role in the transition process of the electricity system to a more efficient and sustainable energy usage. This will include the development within the transportation sector to a growing deployment of electric mobility with (Hybrid) Electric Vehicles (HEV, EV), the emergence of intelligent buildings and smart grids in general.

Energy storage contributes to manage local electricity and heat generation and consumption (self- consumption, smart building), including the integration with other forms of energy use like heating/cooling in an optimal way for the whole power system.

- **Contributing to competitive and secure electricity supply:** Energy storage will play an important role in new market designs, especially flexibility markets and system services as it can provide an economically attractive alternative to grid expansion and load shedding. Specific storage regulation and market mechanisms for flexibility and security of supply will help to create energy storage markets and will contribute to the development of a competitive energy storage industry.

Ultimately it is important to note that the use of energy storage, due to its cross-sector nature, will also affect well-established markets such as the gas market (e.g. power-to-gas), local heat markets (e.g. heat storage), and the transportation market (e.g. electric mobility, fuel cells). The cross-sector ability goes even beyond mere storage and recovery of electricity, and leads to a reduction of carbon emissions in other energy consuming sectors.

⁶ Siemens, ISET, 2008, Design of transport and storage capacities for a future European power supply system with a high share of renewable energies

CHAPTER 4

MISSION AND OBJECTIVES OF THE ROADMAP

4 MISSION AND OBJECTIVES OF THE ROADMAP

The Roadmap aims to:

- Set up recommendations for R&D actions in the timeframe of Horizon2020 and in line with the wider EU 2030 Energy & Climate Framework, which can assist in the integration of renewable energy in Europe and at the same time lead to commercial European manufacturing and international marketing of energy storage devices/facilities.
- Point out European needs and defining major technology areas where R&D is needed.
- Set up milestones for the development over the coming 10-20 year period.
- Provide a framework to help planning and coordinate technology developments within the European energy storage community.
- Give recommendations on strategic stakes aiming at optimising European R&D efforts within energy storage.
- Identify critical energy storage technologies and/or technology gaps that must be filled to meet technology performance targets.
- Identify ways to leverage R&D investments through coordination of research activities.
- Identify regulatory hurdles and market failures preventing the creation of a business case for energy storage.



CHAPTER 5

FUTURE APPLICATIONS AND POTENTIALS RELATED TO ENERGY STORAGE IN EUROPE

5 FUTURE APPLICATIONS AND POTENTIALS RELATED TO ENERGY STORAGE IN EUROPE

5.1 Energy system requirements and added value of storage – technology drivers

Why is Electrical Energy Storage needed in the future energy system?

The need for greater amounts of Electrical Energy Storage (EES) is driven by the need to provide electrical grids with greater flexibility and stability in order to cope with:

- The increase of the peak demand on one hand
- The increase of the level of variable renewable energy on other hand.
- To reduce the level of renewable energy curtailment, thus reducing import dependency on fossil-fuels and improve payback of renewable energy generation investments.
- In a longer perspective EES will be demanded for non-electrical energy uses like transport and heating

EES is not a new concept and has been used successfully for many decades to match the variation in demand with generation, and provide ancillary services. This led to the deployment of Pumped Hydro Storage plants (PHS) that today represents almost 99 % of the worldwide EES storage capacity.

However the ability to use pre-conversion stocks of fossil-fuels coupled with fossil-fuel generators has allowed electrical markets to provide electrical system flexibility without large amounts of Electrical Energy Storage. The increased efficiency, rapid build rates and the known costs of turnkey flexible combined-cycle and open-cycle natural gas turbines has limited the economic competitiveness of PHS. Electrical energy systems therefore tend to rely on fuel based generators to provide system security and flexibility over different time-scales, with the pre-conversion stocks of fossil-fuels providing terawatt hours of chemical energy storage available to be converted into electricity.

Worldwide energy policies aiming at simultaneously reducing CO2 emissions and maintaining or increasing security of energy supplies will drastically change the market rules and drivers for energy systems over the long term. EES must be considered as a critical component of the Future Green Electrical System in order to accommodate ever-greater levels of primary energy from renewable sources.

The defining characteristic of EES in an electricity system is precisely that it allows some deviation between the instantaneous demand for electricity and instantaneous supply.

Indeed, the main EES functionalities include:

- The ability to time-shift electrical energy
- The ability to inject energy to the electrical grid (technically acting as a generator)
- The ability to extract energy from the electrical grid (technically acting as a demand)

EES would therefore be expected to greatly contribute to the achievement of the following targets:

- Security of the power supply of the Electrical System
- Security of power quality
- Cost minimisation: direct & environmental costs through the incorporation of greater levels of primary energy from renewables and therefore the greater substitution of fossil-fuels.

However, EES or ES represent only one possibility, albeit an effective one, among others to provide grid flexibility. There are other alternatives, but one must keep in mind that these are not in themselves exhaustive, and that each addresses a specific separate issue, whereas storage systems have the advantage of providing the solution to a combination of problems. Such options include (but are not limited to):

- Flexible generation systems
- Grid (Transmission/Distribution) flexibility upgrades
- Demand side management
- Interconnection improvement

The main challenge to be overcome in future electrical networks will be the incorporation of ever-greater amounts of renewable energy generation, and the challenge posed by their variable nature providing generation variably and not fully predictable or with a wide seasonal variation. To make matters more complex, the nature of the renewable energy resource varies from Member State to Member State within Europe. In general the Southern states may have a greater reliance on photovoltaic generation with a lesser reliance on wind. Northern states on the other hand may have a greater reliance on wind. The more mountainous states will have a propensity towards hydropower, and coastal states may have an input from wave and tidal. Overall, each Member State is likely to exploit the renewable energy resources that exist within their own boundaries.

Alongside the increased accommodation of primary energy from renewable sources in the period up to 2050 there will be a progressive increase in the electrification of other services too, for example in the electrification of transport and heating systems.

Electrical Energy Storage applications

EES and ES can be integrated at different levels of the Electrical System:

- Generation level: Arbitrage, capacity firming, curtailment reduction
- Transmission level: frequency and voltage control, investment deferral, curtailment reduction, black starting
- Distribution level: voltage control, capacity support, curtailment reduction
- Customer level: peak shaving, time of use cost management, off-grid supply

These different locations in the power system will involve different stakeholders and will have an impact on the associations of services to be provided. Each location may provide a specific share of deregulated and regulated income streams.

The fundamental role of energy storage is to match electrical generation with demand over several timeframes from minutes to months. Energy storage systems have the potential to provide valuable services throughout the energy chain: from power generation, transportation and distribution to the final consumer. Indeed the customer may play an important role in the future energy storage landscape through ownership of energy storage resources either domestically or through vehicle to grid technologies.

Some examples in which energy storage will add value to the electric chain are shown in the following Table 1⁷:

TABLE 1 - Energy Storage segmentation

Conventional Generation	Transmission	Distribution	Customers Services
Black start	Participation of the primary frequency control	Capacity support	End-user peak shaving
Arbitrage	Participation to the secondary frequency control	Dynamic, local voltage control	Time-of-use energy cost management
Support to conventional generation	Participation to the tertiary frequency control	Contingency Grid Support	Particular requirements in power quality
Renewable Generation⁸	Improvement of the frequency stability of weak grids	Intentional islanding	Continuity of energy supply
DG Flexibility	Investment deferral	Reactive power compensation	Limitation of upstream disturbances
Capacity firming	Participation to angular stability	Distribution power quality	Compensation of the reactive power
Limitation of upstream perturbations		Limitation of upstream perturbations	
Curtailment minimisation			

5.1.1 Conventional Generation

- **Black start:** storage can help in the process of restoring a power plant to operation without relying on the transmission network.
- **Arbitrage:** storage optimally selects the production/consumption moments according either to energy market prices (if operating under an electricity market environment) or to technical choices like, for instance, levelling the load (e.g.: in island systems). Storage can also replace expensive and CO₂ emitting peaking capacity.
- **Support to conventional generation:** storage optimises the operation of existing conventional generation assets:
 - › **Generator bridging:** consists in the ability of EES to firm a generator's load while the generator is stopping and until a new generator starts up or the same generator is restarted.
 - › **Generator ramping:** consists in the ability of EES to pick up fast load variations giving enough time for a given generator to ramp-up/-down its production level according to technical limits.

5.1.2 Renewable Generation

- **DG Flexibility:** storage may help renewable generation to contribute to ancillary services: at present, renewable DG operators usually do not participate in ancillary services markets apart from some particular countries (Denmark, Ireland...). For renewable-based DG, contributing to frequency control implies keeping some reserve power, thus "wasting" a part of the down regulation of non-dispatchable RES (curtailment). Hence, when the contribution of renewable-based DG to primary frequency control is compulsory, storage can be considered as an interesting way to provide control power instead of a voluntary degradation of primary energy conversion.

⁷ Table and following descriptions prepared by EASE, T&S Working Group 2

⁸ DG: Distributed Generation

- **Capacity firming:** to support renewable integration, storage can help to increase the dispatchability of variable DG just like conventional generation assets.
- **Limitation of upstream disturbances:** like users of distribution networks, decentralised generators must limit the disturbances they cause. Storage can help in this regard.
- **Curtailement minimisation:** when it is not possible to inject all the energy produced in networks, storage can be charged using this energy and replace the need for fossil-fuels to provide this energy at a later time-period.

5.1.3 Transmission

- **Participation to the primary frequency control:** both DESS (Decentralised Energy Storage Systems) and bulk storage systems can participate in primary frequency control helping to maintain the instantaneous balance between generation and demand. In the ENTSO-E continental European grid, the reserves associated must be released within 30 seconds and maintained for at least 15 minutes.
- **Participation to the secondary frequency control:** storage can participate in adjusting 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. Only the generating units that are located in the area where the imbalance originated should participate in this control.
- **Participation to the tertiary frequency control:** refers to manual changes in the dispatching and commitment of generating units and loads. This control is used to restore the primary and secondary frequency control reserves, to manage congestions in the transmission network, and to bring the frequency and the interchanges back to their target value when the secondary control is unable to perform this last task. Some aspects of tertiary control relate to the trading of energy for balancing purposes and storage can participate.
- **Improvement of the frequency stability of weak grids:** in island systems, the feasible very prompt response of DESS can be interesting from the point of view of frequency stability by helping to avoid load shedding. This application requires a very short response time (<1s) and a discharge duration of a few 10s.
- **Investment deferral:** in case of congestion, the storage units with a capacity of discharge in few hours can be valorised by the resolution of congestions in HTB lines. In long range displacing loads, as terrestrial electrical transport, trains, the presence of medium range static storage systems allows diminishing the feeding points and the load fluctuations of the affected transport lines.
- **Participation to angular stability:** when an accident occurs, some storage technologies can charge and discharge high levels of energy in short periods. Then, they are able to reduce the acceleration of the groups to stop synchronism perturbations. This is a "niche application".
- **Curtailement Reduction and Congestion management:** Storage systems, especially energy intensive solutions such as NaS batteries or hydro, when strategically placed within the grid, can help defer energy production thus reducing the load on critical lines. Given the fact that most intermittent production is concentrated in specific, circumscribed areas, as well as the fact that renewable generation is hardly programmable (e.g. wind farms), the occurrence of backbone congestions is becoming a frequent event.

5.1.4 Distribution

- **Capacity support:** a storage unit is used to shift load from peak to base load periods to reduce maximum currents flowing through constrained grid assets.
- **Dynamic, local voltage control:** DESS may help to maintain the voltage profile within

admissible contractual/regulatory limits. In distribution grids, voltage support can rely both on reactive power (made possible for DESS by power electronics) and active power modulations. The main benefit derives from the deferral of distribution upgrades that would otherwise be necessary to meet the voltage level requirements.

- **Contingency grid support:** performing capacity/voltage support to reduce the impacts of the loss of a major grid component. They might as well be useful in emergency situation, for example after loss of a major component of the distribution grid.
- **Intentional islanding:** it consists in using DESS to energise a non-loopable feeder during an outage. Improving system reliability by energising a feeder during an outage (DESS used as a voltage source).
- **Reactive power compensation:** distribution power quality is made possible by power electronics as well but appears to be a niche application. Reducing the amount of reactive energy drawn from transmission and charged by the TSO to the DSO.
- **Distribution power quality:** with storage, the DSO can maintain the voltage profile in acceptable limits, which increases the quality of supply (less probability of black out or interruptions).
- **Limitation of upstream disturbances:** DSOs have a network access contract with one or more TSO(s), and must therefore limit the disturbances they cause on upstream HV grids to contractual values. If these limits are exceeded, some types of advanced storage systems can help to comply with these commitments by performing active filtering.

5.1.5 Customer Services

- **End-user peak shaving:** energy storage can be used by customers such as industrials for peak shaving in order to minimise the part of their invoice that varies according to their highest power demand. Such a service might be profitable if the peaks are sufficiently predictable and relatively short duration.
- **Time-of-use energy cost management:** a DESS can be charged when the rate is low and be discharged during peak times, with the aim of reducing the invoice of final users. A consumer with a storage unit could be able to contract an Active Demand (AD) service with the DSO or a supplier.
- **Continuity of energy supply:** a storage device is able to substitute the network in case of interruption; this service reduces the damage for industry and householders in case of blackout.
- **Limitation of upstream disturbances:** the customer's contract with a given DSO may account for the limitation of disturbances; the storage can help them to comply with their commitments.
- **Compensation of the reactive power:** a DESS, via the power electronics converter, is able to compensate in local the reactive power.
- **Heat storage:** Heat storing devices – e.g. electrical storage heaters – are able to minimise customer expenses and assist in load levelling
- **Effects from transport**
 - › The development of EV/PHEV will have an impact on the development of batteries for grid storage and end user storage
 - › The development of Fuel Cell vehicles will similarly have an impact on the EES landscape by pushing the development of Power-to-Gas/H₂ storage technologies.

Energy Storage Challenges

As the electrical storage can be located at all places along the value chain and can provide some value simultaneously to different stakeholders, the first challenge is related to the value materialisation because of the following reasons:

- No compensation scheme for storage among stakeholders
- No clear ownership and operating models
- No models for fully capturing different value streams

The second challenge is related to the cost issue in order to position the electric storage technologies in front of the alternative solutions:

- Flexible generation systems
- Grid (Transmission/Distribution) upgrades
- Demand side management

Variable RES integration

The integration of variable RES such as Wind or PV will increase the need for most of the EES applications described before and not only the Renewable Generation segment.

In order to cope with this issue, the ES device could be associated with the RES, with the grid (transmission or distribution) or independently.

The PV is expected to contribute to the development of “prosumers” and aggregators as most of the European PV are located at the end user level.

5.2 Identification of promising technologies for the next decades

The technologies selected for the present Roadmap are those that we judge to have the most promising potential for development to market-based deployment in a time horizon of 10-20 years. Emphasis has been placed on the present industrial maturity and the potential market status for the technologies after appropriate development.

In general, when identifying the technologies of interest in the present document, attention has been paid to the major technical storage properties and their development potential within 20 years. Major inherent technical storage properties in this relation include (in non-prioritised order):

- Energy density (volume and (to a less degree) weight)
- Energy capacity potential (scale of storage facility)
- Power density
- Response / discharge time at rated power
- Power potential
- Efficiency (round-trip)
- Calendar lifetime
- Cycle lifetime
- Cost (including to lifetime)
- Environmental issues including sourcing and building device, working life and recycling potential
- System power ratings
- Safety

In addition we have analysed certain status related market mechanisms and society infrastructure properties, e.g.:

- Level of maturity
- Industrial technology status in Europe
- Development potential
- Research status and potential in Europe
- Possible applications
- Market potential
- Social acceptability

Based on these aspects we have arrived at the technology recommendations given in the following technology sections. For each technologies aggregate, some applications are more relevant than others. The following Table 2 summarise the actual state-of-the-art repartition:

TABLE 2 - Summary actual state-of-the art repartition

Technologies aggregate in focus	Conventional generation	Renewable Generation	Transmission	Distribution	Customers services
Pumped hydro energy storage	●	●	●	●	●
Compresses air energy storage	●	●	●	●	●
Electrochemical	●	●	●	●	●
Chemical	●	●	●	●	●
Electro-magnetic Energy Storage, Flywheels	●	●	●	●	●
Thermal energy storage	●	●	●	●	●

● Suitable ● Possible ● Unsuitable

One of the biggest R&D challenges for the next decade will be to transform “possible” or “unsuitable” applications to “suitable” and increase the range of service each storage technologies can deliver in order to multiply applications for a given storage solution. One way of doing that could be to use hybrid technologies solutions (i.e. using complementary technologies in one single storage site).

Moreover it is important to note that the recommendations given in the present Roadmap should not preclude supplementary R&D interest and resources in other technologies that are not presently believed to hold a commercial potential in the 10-20 year period. Technical breakthroughs in other storage technologies may completely change the basis for the present recommendations.

5.3 European competences within energy storage – industry and research

The storage of energy has a long and distinguished history in Europe and consequently European competences are strong and widespread. Along with the rest of the world, Europe is engaged in a race to up-scale storage technologies to enable energy to be stored in large enough quantities to stabilise electrical grids and to enable the electrification of a large part of the world's transport fleet.

It can be argued that the main barriers to rapid progress have been a lack of strategic thinking in research. This has created duplication of effort and some potentially interesting new ideas may have been overlooked. Also, it is often noted that Europe lags behind many other countries and associations in the evolution of promising research into industrial products. Nevertheless, Europe holds strong competences worth building on within a significant number of promising storage technologies:

Chemical Storage

Principally through hydrogen, chemical storage is an area that has shown rapid development in Europe in recent years. Considerable funding from both EU and the member states has created a vibrant research community in the production (electrolysis), storage and conversion (fuel cell) of hydrogen. As with batteries new innovative materials and devices have created a range of technological options for exploitation for industry.

Electrochemical Storage

Even if the European position is strong in the Lead-Acid & Ni-Cd field, the situation is different for the Li-ion technology that is currently dominated by Asian actors (Japan, Korea, China) because of its use in numerous consumer products (e.g. mobile phone, portable PC). Furthermore, the weakness of the Japanese grid contributes a lot to the fact that there is only one NaS supplier located in Japan. However, the joint development of the European Battery market for transport and stationary applications represents a big opportunity for strong industrial suppliers (e.g. Saft, Fiamm) supported by a strong European R & D network to be able to compete against the Asian industrials in a field where European competences are rapidly increasing. Electrochemistry is the core technology in batteries, electrolysis, super capacitors and fuel cells and this implies a close linking of core research activities to industrialists. A survey of the participating laboratories in EERA shows that Europe has strength in electrochemical research in terms of innovative materials, chemistry and battery design. The EERA project is already beginning to show how these laboratories can strategically align their research and so further improve rates of discovery.

Mechanical Storage

Compressed Air Energy Storage (CAES) is another field, where European industrial technology is arguably world leading. CAES is judged to have an enormous potential and one plant, out of two in the world (the other in Alabama, USA), is located in Germany and operated by E.ON Kraftwerke. This 290 MW plant was constructed in 1978 and has been in operation ever since. Additionally the European competences are of extremely high class within crucial areas like compressor and turbine technology as well as solution mining, which is of central importance also for storing gases (e.g. hydrogen or synthetic methane) prepared by electrolysis via electricity from renewable sources (see also below). Europe is in ideal position to exploit any future expansion in this market.

Pumped Hydro Energy Storage is the largest storage technology in Europe (indeed, world-wide). In 2009 the European Union (EU27) had 41.3 GW net pumped hydro storage capacity (34% of world capacity) out of a total of 103 GW of hydropower and representing 5% of total net electrical capacity in the EU⁸. This capacity has been established by European industrial competences within construction works and hydroelectric equipment technology. The existing facilities illustrate a topic where significant potential (quantitative as well as qualitative) for new expansion and development exists.

Kinetic Energy Storage based on Flywheels is a technology of energy storage considered as a fast energy storage technology, a particular type within the group of technologies, with the main characteristics of high power and energy densities and the possibility to decouple power and energy in the design stage. Moreover 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, are other important characteristics.

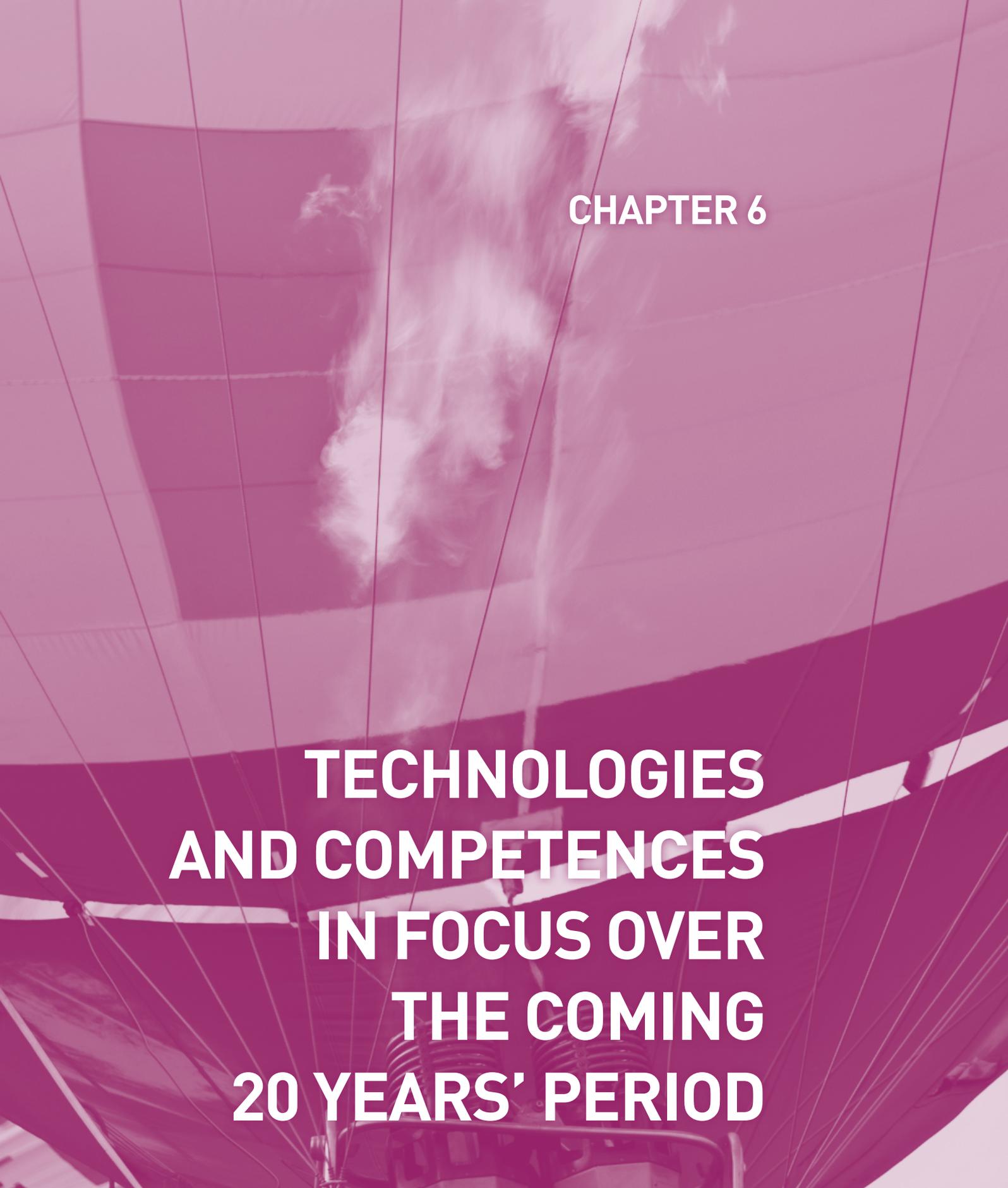
Thermal Storage

Thermal Storage has been utilised effectively for many decades in Europe based formerly on sensible heat storage in simple systems. However, new developments are rapidly emerging in laboratories all over Europe aiming for new materials and systems. Examples of new successfully commercialised thermal storage systems are Underground Thermal Energy Storage (UTES) being deployed particularly in the Netherlands, Sweden and Germany and the 1000 MWh molten salt storage technology which makes dispatchable power generation by CSP plants feasible. In addition European industrial products are already marketed with focus on improved materials and focus on customer services in the future electricity market with highly volatile electricity prices.

Electrical Storage

Superconducting magnetic energy storage has been of scientific interest for years and still needs a considerable development effort to demonstrate the practical potential. Long term rather basic R&D effort is required, but on the other hand the technology may hold a considerable potential. Energy storage based on superconducting coils has been developed for small to medium size systems. The most outstanding performances are high short-term power at high overall efficiency (>95%), high robustness and long lifetime with an almost unlimited number of cycles. The use of High Temperature Superconductors and the combination with long-term energy supply based on liquefied hydrogen (LIQHYSMES) should offer very competitive multi-functionality hybrid solutions. Europe has competences and activities going on within the field, which are valuable for a future development and eventual commercialisation of the technology.

8 <http://www.eia.gov/cfapps/ipdbproject/iedindex3.cfm?tid=2&pid=82&aid=7&cid=regions&syid=2004&eyid=2010&unit=MK>



CHAPTER 6

TECHNOLOGIES AND COMPETENCES IN FOCUS OVER THE COMING 20 YEARS' PERIOD

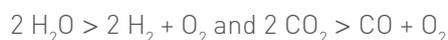
6 TECHNOLOGIES AND COMPETENCES IN FOCUS OVER THE COMING 20 YEARS' PERIOD

6.1 Chemical Energy Storage

Chemical energy storage is the transformation of electrical energy into chemical energy carriers. It consequently involves exchange of energy between different vectors of the energy system. Once the energy is transformed to chemicals the concept opens for many ways to use the primary electric energy, e.g. for re-electrification, heating and mobility. For the 20 years period considered in the present roadmap the development of chemical energy storage will involve development of the entire process chain including electrolysis in some form, storage as well as efficient chemical reactions to form fuel or chemical feedstock for stationary and mobile applications.

a) Electrolysis

The electrolytic processes of interest will be dissociation of water or – depending on the coming development effort and capture of CO₂ – dissociation of CO₂. The two reactions, which both require input of electrical energy are:



Electrolyser technology for the first reaction is very well known and has been utilised for about a century (though not in multi-MW scale) whereas the second reaction can be achieved through high temperature ceramic electrolyser technology based on solid oxide or perhaps electrochemical cells based on lower temperature electrolytes currently at research level.

The most promising low temperature technologies are based on liquid alkaline electrolyte or solid polymer exchange membranes (PEM).

b) Chemical energy carriers

The most appropriate fuel will depend on the type of energy application (stationary or mobile), the type of chemicals used elsewhere in the energy system, and legal requirements e.g. on emission of harmful reaction products. In the case of hydrogen, it can either be stored at cryogenic temperature in its liquid form, in its gaseous state up to 700 bars or in solid state materials e.g. hydrides under relatively low pressures.

Hydrogen has an extended versatility of use, can be efficiently reconverted to electrical energy giving only harmless water vapour as a reaction product and can be transmitted in dedicated pipes to connect several production sites or admixed into the existing natural gas network to a certain limit.

c) Final conversion process

By reaction with captured CO₂ hydrogen can be converted to synthetic methane in a catalytic process (methanation) or to liquid fuels via Fischer-Tropsch processes. Hydrogen can also react with captured nitrogen (Haber-Bosch process) to form ammonia.

Maturity of technology chain components

The below figure shows the technical maturity of various parts of chemical storage option:

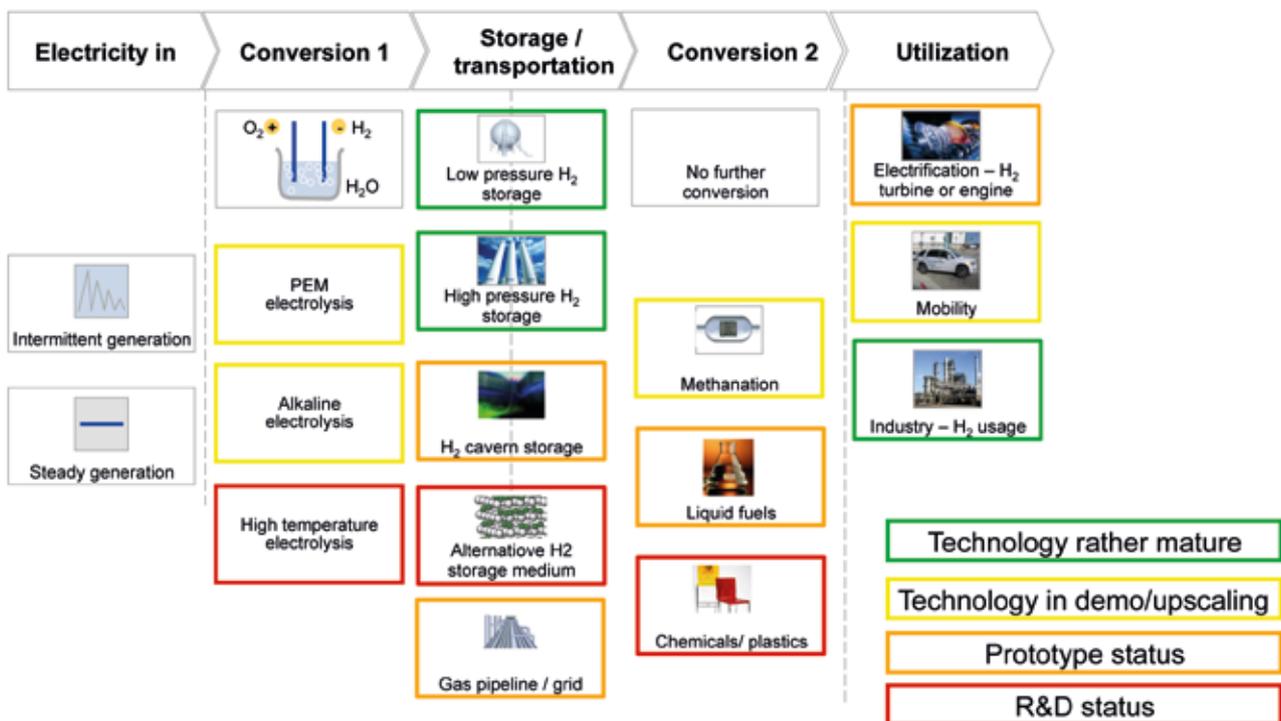


FIGURE 1: Technical maturity chain components

Applications

Chemical energy storage has a huge storage potential due to its high energy density and the opportunity of using large scale storage facilities e.g. underground. This possibility allows the use of electrolyzers for **energy arbitrage, grid services and even seasonal storage**. At the same

time electrolysis to form chemical energy will transform renewable energy into CO₂-neutral fuels for light and heavy transport applications, when this becomes more pressing at some point in the future. Similarly electrolyser technology opens for the possibility of manufacturing organic chemical compounds widely used by European chemical industry already now depending today on fossil sources.

Electrolysers are fast-reacting devices. Once a voltage is applied above the equilibrium voltage on the electrodes gas evolution starts immediately and vice versa. Existing experience with electrolysers clearly shows that they have the ability to react within a second or lower upon changes in electricity supply/demand, both up and down. Electrolysers are therefore well suited for provision of many types of ancillary services for the future electrical grid with high penetration of renewables including primary operational reserves. For electrolysers operating at temperatures highly above ambient, the short term balancing capability requires, that the plant is kept at operating temperature even when idle.

SET Plan targets⁹ for electrolysis and hydrogen storage technologies towards 2030 and beyond

» Alkaline Technology

TABLE 3 - 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 (bars)	1-200	1-350	1-700
Durability (h)	10 ⁵	> 10 ⁵	> 10 ⁵
Cyclability	Poor	improved	high
Production capacity of electrolysis	Up to 50 kg/hour (≈ 500 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

⁹ http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

» PEM Technology

TABLE 4 - SET Plan targets PEM Technology

Property	State-of-the-art	Target 2020-2030	Ultimate goal
Operating current density (A/cm ²)	0 – 1	0 – 2	0 – 5
Operating temperature (°C)	50-80	80-120	100-150
Operating pressure (bar)	1-50	1-350	1-700
Enthalpic efficiency with PGM catalysts	80% at 1 A/cm ²	80% at 2 A/cm ²	80% at 4 A/cm ²
Enthalpic efficiency with non-PGM catalysts	30-40% at 1 A/cm ²	60% at 1 A/cm ²	60% at 1 A/cm ²
SPE Voltage drop (mV at 1 A/cm ²)	150	100	67
SPE ionic conductivity (S/cm at 80°C)	0.17	0.20	0.30
SPE gas permeability to H ₂ (cm ² /s.Pa) [80°C, full humidity]	10 ⁻¹¹	10 ⁻⁹	10 ⁻⁹
Cathodic PGM (Pt) content (mg/cm ²)	1.0-0.5	0.5-0.05	< 0.05
Anodic PGM (Ir, Ru) contents (mg/cm ²)	1.0-2.0	0.5-0.1	< 0.1
Durability (h)	10 ⁴	10 ⁴ – 5·10 ⁴	> 10 ⁵
Production capacity of electrolysis units	1 kg/hour (≈ 10 Nm ³ /hour)	> 10 kg/hour (≈ 100 Nm ³ /hour)	> 100 kg/hour (≈ 1000 Nm ³ /hour)
Energy (kWh/kg H ₂ at 80°C, 1 A.cm-2)	56	< 50	48
Non-energy cost (€/kg H ₂)	5	2	1

» Solid Oxide Technology

TABLE 5 - 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 (bars)	1-5	1-30	1-100
Operating current density (A/cm ²)	0-0.5	0-1	0-2
Area Specific Resistance (Ω.cm ²)	0.3-0.6	0.2-0.3	
Enthalpic efficiency	100% at 0.5 A/cm ²	100% at 1 A/cm ²	100% at 2 A/cm ²
Cell voltage degradation (at 1 A/cm ²)	> 10 %/1000hrs	< 1 %/1000hrs	< 0.1 %/1000hrs
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 (hours)	12	1-6	< 1-6
Shut down time	Few hours	Few minutes	Few minutes
Start-up /Shut down cycles	< 10	100	1000
Production capacity	<1 kg/hour (≈ 10 Nm ³ /hour)	10 kg/hour (≈ 100 Nm ³ /hour)	100 kg/hour (≈ 1000 Nm ³ /hour)
Non-energy cost (€/kg H ₂)	5	2	1

» Hydrogen Storage Technologies

TABLE 6 - 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 storage technology are related to costs, but also technical aspects are still not sufficiently developed:

1. Investment costs (EUR/kW) need to be reduced to expand application areas
2. Efficient large scale components are not always sufficiently available
3. High pressure compression of hydrogen from atmospheric pressure electrolyzers is expensive
4. Lack of up-scaling experience, e.g. system optimisation packaging and large-scale dynamic response ability
5. Efficiency of electrolysis at high cell current density is too low
6. Efficiency of chemical processes to form other synthetic fuels from hydrogen is too low
7. Hydrogen storage materials still in R&D status

Research needs

Improving chemical energy storage performance requires a spectrum of efforts as follows:

1. Materials research and development to
 - a. Identify new low cost materials for cell frames, electrodes, catalysts, membranes and electrolyte.
 - b. Industrially optimise the manufacturing of components, which will partly require higher number of electrolyzers manufactured (automatisation)
 - c. Improve durability (for high temperatures: active and robust materials as well as cell construction materials)
 - d. Reduce degradation of cells over time of use
2. Testing large scale (MW) components via pilot and demonstration projects and programmes
3. Dedicated research and development efforts on high-pressure electrolysis. Currently available technology yields about 30 bars. Higher pressure is needed to better meet filling pressure of storage tanks and caverns ranging from 200 bars (underground caverns) to 700 bars (tanks in passenger vehicles).
4. Materials and electrochemical process research and development to
 - a. Describe and understand electro-catalytic exchange processes on interfaces in the electrolysis cells
 - b. Improve cell and stack design
 - c. Obtain large area cell fabrication and durability of the cells
 - d. Reduce internal resistance of cells
 - e. Further development of high-temperature solid oxide electrolyzers
 - f. Further development of catalysts for low temperature electrolysis

5. Materials research and development to
 - a. Identify new low cost materials for storage of hydrogen in solid state with improved storage density and cycling durability (cost optimisation)
 - b. Develop cost-efficient tanks for high pressure storage of hydrogen
 - c. Describe, understand and improve thermal management of hydrogen storage materials
 - d. Demonstrate optimised integration of tanks based on selected types of solid state hydrogen storage materials with different applications (stationary, transport and portable)

6. Experience from demo-projects concerning:
 - a. Up-scaled system integration in a compact and safe grid connected facility with no restrictions concerning location and public acceptance
 - b. Large-scale experience with dynamic properties of electrolyser plants
 - c. Use of existing infrastructure for distribution and storage of hydrogen and determination of limits in the existing infrastructure (natural gas transmission and distribution network, as well as underground storage facilities)
 - d. Safety issues including new storage media that can store hydrogen in a safe and compact way

7. Research and industrial optimisation of catalytic formation processes for chemical fuels by conversion of hydrogen and CO₂

8. Research on electrochemical synthesis of ammonia, methanol, ethanol, formic acid and other chemicals

Resources and infrastructure

In a short time perspective investment will be required for the entire chain from the development of electrolysers to storage technologies. Due to the high risk of investments the topic will require public support to become a significant part of the European energy system. In a longer time perspective the issue of support system should be dealt with in the framework of a new market design for the energy system.

6.2 Electrochemical Energy Storage

Batteries

Batteries are electrochemical energy storage devices based on a variety of different specific chemical systems: Today the most commonly used technologies on the market available are lead-based, lithium-based, nickel-based and sodium-based batteries. They are used in and tailored for a variety of different applications. Batteries have been practically utilised as convenient power sources for about two centuries and the application range of rechargeable batteries has been dramatically expanding over the latest decades because of increasing demand for stationary and mobile power sources in numerous appliances and other devices. These technologies have been progressively developed over the years to meet the evolution of specific and increased requirements for each application, resulting in specific advanced battery products to be used in applications for which they are designed.

Batteries are based on single electrochemical cells each having voltages in the range from below 1 V up to about 4 V. The cells can be combined in series to yield very high voltages if required. Batteries hold highly attractive power densities and their round cycle efficiency (electrical energy out over electrical energy in) are 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. The cells use chemical reaction(s) to create a flow of electrons – electric current. Primary elements of a cell include the container, two electrodes (anode and cathode), and electrolyte material. The electrolyte is in contact with the electrodes. Current is created by the oxidation-reduction process involving chemical reactions between the cell electrolyte and electrodes.

When a battery discharges through a connected load, electrically charged ions in the electrolyte that are near one of the cell electrodes supply electrons (oxidation) while ions near the cell other electrode accept electrons (reduction), to complete the process. The process is reversed to charge the battery.

Maturity of technology

Electrochemical energy storage in batteries is basically a mature technology, since it has been utilised for more than a century based on industrial products. However, as described above, batteries have many shortcomings in a variety of use cases. As an example, Li ion battery technology can be called mature in the sense that it is already used widely in a spectrum of applications and yet it is immature in the sense that improved performance is demanded for other new applications, such as those in electricity grids.

Batteries are well established on markets for mobile and stationary power sources. The annual European and Middle East (EMEA) market size is approaching 1 billion EUR¹⁰ (EUROBAT members) as electricity storage devices and can be expected to increase over many years to come. If the technical performance of batteries is further improved, as targeted by this Roadmap - the market demand will become enormous.

However, significant scientific and technological progress is still needed on various competing and emerging batteries to move them to the market place, as reported in Table 7. Information has been collected from multiple sources^{11 12 13 14}.

10 http://www.eurobat.org/sites/default/files/website_industrial_statistics_2012.pdf

11 J. Eyer e G. Corey, "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide", Sandia National Laboratories, Report SAND2010-0815, February 2010.

12 R. Alanen et altri, "D4.1 Electrical Energy Storage Technology Review", EERA Joint Programme on Smart Grids, Sub-Programme 4 "Electrical Storage Technologies", March 2012.

13 S. Inage, "Prospects for Large-Scale Energy Storage in Decarbonised Power Grids", Report IEA (International Energy Agency), 2009.

14 EUROBAT White Paper – Importance of Battery Energy Storage for Renewable Energy Supply, November 2011.

TABLE 7 - Status of development of major electrochemical storage systems for grid applications

Status	Electrochemical Energy Storage
Mature	Lead-acid
Commercial	Lead-acid, NaS (sodium-sulphur)
Demonstration	ZnBr (zinc bromine), advanced lead-acid, VR (vanadium redox), NiMH (nickel-metal hydride), Li-ion (Lithium-ion)
Prototype	Li-ion, FeCr (Iron Chromium), ZEBRA (sodium nickel chloride = Na-NiCl ₂)
Laboratory	Zinc-air, advanced Li-ion, new electrochemical couples (other Lithium-based)
Idea -concept	Nano Supercapacitors, new electrochemical couples (metal-air, Na-ion, Mg-based and so on)

Applications

Electrochemical storage systems are estimated to be one of the key storage technological enablers of the transition from the current mostly centralised electricity generation networks to distributed ones with increasing penetration of variable and not programmable renewable energy sources (e.g., wind and photovoltaic) and more “intelligent” management of the energy flows (with Smart Grids and “pro-users”, who are end-users with more active role in the electricity market).

A schematic comparison, as presented in Table 8, of the key applications with the various electrochemical storage competing technologies shows the extreme variability of possibilities and the effective suitability¹⁵.

TABLE 8 - Comparison among different electrochemical storage systems for the key grid applications

Application	Pb acid	Ni/MH	Na/S	Na/NiCl ₂	Redox Flow	Li/ion	Super capacitor
Time-shift	●	●	●	●	●	●	●
Renewable integration	●	●	●	●	●	●	●
Network investment deferral	●	●	●	●	●	●	●
Primary Regulation	●	●	●	●	●	●	●
Secondary Regulation	●	●	●	●	●	●	●
Tertiary Regulation	●	●	●	●	●	●	●
Power System start-up	●	●	●	●	●	●	●
Voltage support	●	●	●	●	●	●	●
Power quality	●	●	●	●	●	●	●

● Suitable ● Less suitable ● Unsuitable

¹⁵ RSEview, L'accumulo di energia elettrica, (in Italian), Il Melograno Editore, December 2011.

Table 8 qualitatively also presents the competition in place among storage technologies, but does not give any description of the real status of development in economic and technical terms in relation to the various grid applications.

The current worldwide energy storage capacity installed in electricity grids is estimated in about 127,000 MW, of which 99% is made with pumped-hydro systems. The electrochemical storage amounts to about 446 MW, made of Na-S (365), lead-acid (35), Ni-Cd (27), Li-ion (16) and redox flow (3).

The most imminent business cases for grid application of batteries are expected to arise from demand for grid services in consequence of still larger penetration of renewable fluctuating energy sources in Europe and the parallel phasing out of fossil plants, which have until now taken care of the services.

Also decentralised application of batteries in the low voltage end of distribution grids is expected to become an early business case following the dramatic increase in solar power installations seen all over Europe. Local solar power may lead to constraints in the low-voltage grid, which can be prevented by local storage capacity (battery) and thereby defer reinforcement of the local grid, which is often an expensive path.

Batteries are already well established on the market for different mobile and stationary power applications. According to a very recent market analysis by BCC Research, large and advanced batteries represented a \$15.3 billion global market in 2009 and \$16.7 billion in 2012¹⁶. BCC projects a market of more than \$21 billion by 2017 and a compound annual growth rate (CAGR) of 4.6% between 2012 and 2017 making it one of the largest and fastest-growing, technology-driven electrical/electronic sectors. The term “large-and-advanced batteries” introduced by BCC means secondary (rechargeable) electrochemical energy storage devices, “large” in terms of size and capacity and technologically advanced. So this definition excludes all primary and lead-acid automotive batteries as well as small-size cylindrical and button cells.

¹⁶ bcc research, Large and Advanced Battery Technology and Markets, February 2013

¹⁷ http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

SET Plan targets¹⁷ for batteries towards 2030 and beyond

TABLE 9 - SET Plan targets for batteries towards 2030 and beyond

System	Current performance	Target 2020-2030	Target 2050
Li ion/Energy version	Max. 241 Wh/kg – 535 Wh/L (Co based); ca. 500 cycles Safe : 130 Wh/kg –	ca. 180-350 Wh/kg – 350-800 Wh/L Safe >. 10000 cycles	> 350 Wh/kg - > 800 Wh/L Safe > 10000 cycles
	300 Wh/L (LFP based); ca. 2000 cycles -20, +60°C ca 500-1000 €/kWh (or 25 c€/kWh/cycle)	-20, +70 °C ca 200 €/kWh (or 10 c€/kWh/cycle) i.e. phosphates < 10 €/kg or lamellar oxides < 20 €/kg; separator < 1 €/m ²	-20, +70 °C < 200 €/kWh
Li ion/Power version	50-90 Wh/kg – 105-190 Wh/L ca. 3 kW/kg ca. 10000 cycles -10, +60 °C > 1000 €/kWh	170-220 Wh/L >5 kW/kg Safe >. 15 years -20, +70 °C ca 20 €/kW i.e. LTO < 10 €/kg	> 100 Wh/kg – 220 Wh/L ca. 10 kW/kg Safe > 15 years -20, +70 °C ca 20 €/kW or <
Redox Flow Batteries (Vanadium, ZnBr ₂) 10-20Wh/kg – 15- 25Wh/L (Vanadium);	10-20 Wh/kg – 15- 25 Wh/L (Vanadium); 10-20 years >10000 cycles) 10, +40 °C 50-60 Wh/kg (ZnBr ₂ based); >2000 cycles Projected service cost (Capex and Opex) 10 c€/kWh Energy cost 400 €/kWh Power cost 600 €/kW	Gen2 Vanadium Bromide 20-40Wh/kg Wider operating T° range >100°C) Projected service cost (Capex and Opex) 7 c€/kWh Energy cost 120 €/kWh Power cost 300 €/kW	Reduction of total system cost (Capex & Opex) Projected service cost (Capex and Opex) 3 c€/kWh Energy cost 70 €/kWh Power cost 200 €/kW
Metal air systems	700 Wh/kg (Li air Polyplus) Poor Cycles	> 500 Wh/kg 300-500 €/kWh 3000 cycles	500-1000 Wh/kg 10000 cycles ca. 100 €/kWh
Na-Ion		Expected decrease in battery cost ~40%	
Li-S	350 Wh/kg – 350 Wh/L (Sion Power) High self-discharge 4- 6%/month (sulphur migration), poor life cycle (60-100 cycles) and safety issue -40 °C-25 °C	500 Wh/kg 3000 cycles < 350 €/kWh	600 Wh/kg 10000 cycles ca. 200 €/kWh

Additional target information for Electrochemical Energy Storage technology towards 2030

Targets for Lead technology for the period 2020-2030:

- Energy cost < 150-100 €/kWh or < < 0.08-0.04 €/kWh/cycle
- Temperature operating range for stationary applications: -30 to +60°C
- Specific performances: 60-100 Wh/kg and 140-250 Wh/L
- Cycle life: > 3,000 (80% DoD) -10,000 cycles (60% or 80% DoD)

Targets for Nickel technology for the period 2020-2030:

- Energy cost < 250-1,000 €/kWh
- Temperature operating range for stationary applications: -40 to +70°C
- Specific performances: 60-140 Wh/kg up to 80-200 Wh/kg and 80-450Wh/L up to 100-600Wh/L
- Cycle life: > 6,000 - 8,000 cycles (80% DoD)

Low cost technology targets for high temperature batteries (sodium-based) with a substantially increased cyclability (in excess of 10,000 complete charge/discharge cycles).

The following installed cost targets (set for everything needed up to direct current output to the converter) reflect the push and pull of the energy storage market:

- Current: \$3,000/kW
- 2020: \$2,000/kW
- 2030: \$1,500/kW

The following range of lifecycle costs could also help achieve system targets:

- Current: \$0.04-\$0.75/kWh/cycle
- 2020: \$0.01-\$0.27/kWh/cycle
- 2030: \$0.01-\$0.08/kWh/cycle

Low cost technology targets for redox flow:

- Targets for the period 2020-2030: Energy cost 120 €/kWh and Power cost of 250 €/kW.
- Temperature operating range -20°C to +60°C, while maintaining the rest of the figures in values similar to current Vanadium technology: 15-25 Wh/L, > 10,000 cycles.

Targets for Li ion technology for the period 2020-2030:

- Energy cost < 200 €/kWh or < < 0.10 €/kWh/cycle and Power cost <20 €/kW.
- Temperature operating range for mobile applications: -20 to +60°C
- Temperature operating range for stationary applications: 0°C to 40°C
- Specific performances: 180-350 Wh/kg and 350-800 Wh/L, > 5,000 cycles (100% DoD).

Gaps between targets and present performance

- For batteries as mobile and stationary power sources the most critical gaps between needs and present standard performance over the coming 10-20 years are:
 - > costs
 - > energy density
 - > power performance
 - > lifetime - degradation during shelf storage as well as during use
 - > charging capabilities

- Even though batteries have been strongly demanded over decades for critical applications, e.g. military, communication and transport, present battery technology still displays energy densities between one and two orders of magnitude lower than traditional chemical energy carriers (e.g. hydrocarbons).
- Batteries for grid applications should in the first place to be considered as stationary installations to be specifically developed to fulfil functionalities for grid balancing, such as supporting primary and secondary reserve power, contributing to reserve capacity building and ancillary services to support transmission. Batteries have high potential because their flexibility in sizes and characteristics but can only contribute efficiently if correctly designed and tailored to contribute to time-shifts, peak shavings and in particular to support capacity firming of intermittent renewable sources. For stationary grid applications, most important properties to improve are cycle life time and calendar life time in order to develop reliable and costs-effective products.
- Whereas batteries in EVs cannot solve the grid issue alone, some smart grid plans in Europe include batteries in electrical vehicles, the idea being to use batteries on board vehicles as a balancing component (G2V and V2G) in the grid. In this case the property gap for batteries is particularly insistent. Battery electrical vehicles are marketed with driving range up to 150 km, which is in practice usually even considerably lower due to need for auxiliary power in the vehicles (defrosting, cabin heating, air conditioning etc.) as well as weather conditions and road friction. The chances that batteries in vehicles can play the described balancing role in the electrical grid depend on the consumers' demand for those vehicles and this will in turn be stimulated by improved battery technology in the form of longer charging intervals (higher energy density in the battery) and lower charging times (more rapid chemical reactions and faster transport within the battery). Further logistical obstacles must be overcome, including ways to avoid compromising the battery warranty provided by car manufacturers to their customers.

Research needs

- Intensive materials research will be required for substantial breakthroughs and increased applicability for batteries to grid applications for all mature battery technologies (Lead-based, Lithium-based, Nickel-based and Sodium-based batteries) should be considered, as each technology has the potential for significant further technical improvement, and can all provide distinctive and important functions to grid operators.
- Research should be directed both at improving performances at the battery cell level, and battery system design level (connectors, 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. It should also include focused research on intelligent battery management, including the electronics and systems for quality control and battery "smartness".
- Immediate priorities to include are improvements to the cycle life and overall calendar life of advanced batteries addressing the relevant degradation mechanisms. Advanced lead, nickel, Sodium and lithium batteries have still high potentials that should be further developed increasing the safety of Li-ion batteries and extending their temperature range of operation (from -20 to +60 °C).
- Exploratory research is strongly recommended on novel materials for completely new electrochemical systems (e.g., metal-air, liquid batteries, Mg-based batteries, fluoride-ion, chloride-ion, other conversion-based systems, battery cell up to 5V,) with the additional targets for the 2020-2030 period to further reduce the battery cost of more than 40%. In general, the targeted technical and economical performances of the emerging electrochemical technologies may be estimated to be in the horizon 2020-2030: more than 500 Wh/kg, more than 3000 complete charge/discharge cycles and a cell cost below 350 €/kWh.

- Software development of many kinds aiming to model and control battery technologies and thus facilitate integration of electrochemical storage devices into the electricity system.

Resources and infrastructures

A predominantly research-directed effort on improved or brand new electrochemical storage systems is required and an appropriate funding size range of at least 50-70 M€ per year would be necessary to reach significant improvements. This estimated effort is aimed at supporting research laboratories focused on basic and applied materials research and electrochemical development, with advanced research infrastructure and modelling tools, up to complete investigation of safety and degradation mechanisms up to complete engineering and full scale demonstration, and European industry is foreseen to contribute with only a minor part.

Electrochemical capacitors (supercapacitors)

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 quite properly referred to as electric double layer capacitors (EDLC). This mechanism is highly reversible, therefore ECs, exactly as conventional capacitors, can be charged and discharged thousands of times. Electrode surface area in capacitors determines the capacitance and thus, the energy storage capability of the device. The amount of energy stored by ECs is very large compared to a standard capacitor because of the enormous surface area created by the porous carbon electrodes and the very small charge separation created in the double layer.

Maturity of technology

Supercapacitors have a short history dating back to the first discoveries in 1957. Niche uses have been seen since early 80ies and a broader use of ECs have accelerated over the last 15 years in particular. However, a large development potential still exists and from this point of view the electrochemical capacitor technology must be characterised as immature.

Applications

ECs are very suitable for high-power applications with 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 distribution voltages up to 600 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, for example:

1. **Transmission line stability.** The stability of a transmission system 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 100MW with 500 MJ (< 5 s).

2. **Spinning reserve.** This is the generation capacity that a utility holds in reserve to prevent service interruptions if a generator fails. An ultracapacitor system can be built to supply power during the interruption, until quick-start diesels begin to supply power. A typical specification is 20MW to 100MW and 300 MJ to 1500 MJ.
3. **Area and frequency control.** The lack of matching between electrical energy production and energy consumption (including losses) appears as a frequency variation. EC system, thanks to its 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.

SET Plan targets¹⁸ for supercapacitor technologies towards 2030 and beyond

TABLE 10 - SET Plan targets for supercapacitor technologies towards 2030 and beyond

Current performance	Target 2020-2030	Target 2050
< 10Wh/kg (close to 5 Wh/kg) 10-20kW/kg (1-5 s) ca. 1500-2000 m ² /g > 10000 cycles (> 100000 cycles depending on systems) Low °C [-40 °C]	>10-15 Wh/kg ca. c€/F	Electrolyte stability ca. 4.5-5V ca. 3000m ² /g active area ca. 600 F/g Energy close to power batteries (50 Wh/kg)

Supercapacitors, (EDLC, pseudo capacitors like oxides, hybrid or asymmetric systems...)

Economic targets for supercapacitor technology towards 2030

Table 10 reports the proposed SET Plan targets, which have been more numerically addressed for the period 2020-2030.

TABLE 11 - Economic SET Plan targets for supercapacitor technology towards 2030

Current performance	Target 2020-2030	Target 2050
< 10Wh/kg (close to 5 Wh/kg) 10-20kW/kg (1-5 s) ca. 1500-2000 m ² /g > 10000 cycles (> 100000 cycles depending on systems) Low °C [-40 °C]	>10-15 Wh/kg ca. c€/F <i>More precisely and challenging: much less than 1 Eurocent/F, corresponding to an energy cost of less than 3 €/Wh and a power cost of less than 0,3 €/W, specific performances: >10-15 Wh/kg, while maintaining similar high power capability and long cycle life as current ECs.</i>	Electrolyte stability ca. 4.5-5V ca. 3000m ² /g active area ca. 600 F/g Energy close to power batteries (50 Wh/kg)

Supercapacitors, (EDLC, pseudo capacitors like oxides, hybrid or asymmetric systems...)

¹⁸ 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 power in a small volume and weight with high stability for a long time. The storage system round-trip efficiency is extremely high, around 95%.

The low energy density and high capital costs (estimated in the range of 1100-2000 €/kW)¹⁹ limit the use of SCs in electricity grids to high-power applications (up to 10 MW) with 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 distribution voltages up to 600 V.

Research needs

- Finding electrolytes capable of voltages beyond 2.7V, preferably with less toxicity. One route to achieve this will be the development of ionic liquids for higher voltage ranges with wide operational temperature range and high conductivity. Ionic Liquids-solvent mixtures with high voltage solvents as developed in Li ion batteries (additives/new solvents);
- Proof of concept of asymmetric Li Ion Capacitor (LIC) systems: improve life cycle and improve symmetry of charge-discharge rates to achieve 20-30Wh/kg in synergy with high power Li-ion batteries; proof of concept of ceramic EC with dielectric or insulator with very high permittivity;
- Basic and applied research on aqueous hybrid systems at a very low cost and with low environmental impact using activated carbons;
- There are extraordinary opportunities for taking advantage of materials that exhibit pseudocapacitance to produce high-performance ECs. Improved understanding of charge transfer processes in pseudocapacitance is a critical step that will lead to the design of new materials and multifunctional architectures offering substantially higher levels of energy and power density. Novel transition metal oxides of lower cost and better performances need to be explored for EC applications because of their layered structure and ability to adopt wide variety of oxidation states.
- Unlike oxide materials, which have been extensively studied for supercapacitors, nitrides and sulphides have received limited attention. Conventionally, some nitrides are known to have better conductivity than oxides and are hence more suitable for high rate devices like capacitors.
- Reducing component and finished electrode material manufacturing costs,
- Increasing the capacitance of electrodes by increasing surface area and tailoring the pore size and shape.

Figure 2 summarises the roadmap of ECs with projections towards 2030, in which the future visions on development of new high performance materials for electrodes and electrolytes are evidenced.

¹⁹ S. Inage, "Prospects for Large-Scale Energy Storage in Decarbonised Power Grids", Report IEA (International Energy Agency), 2009

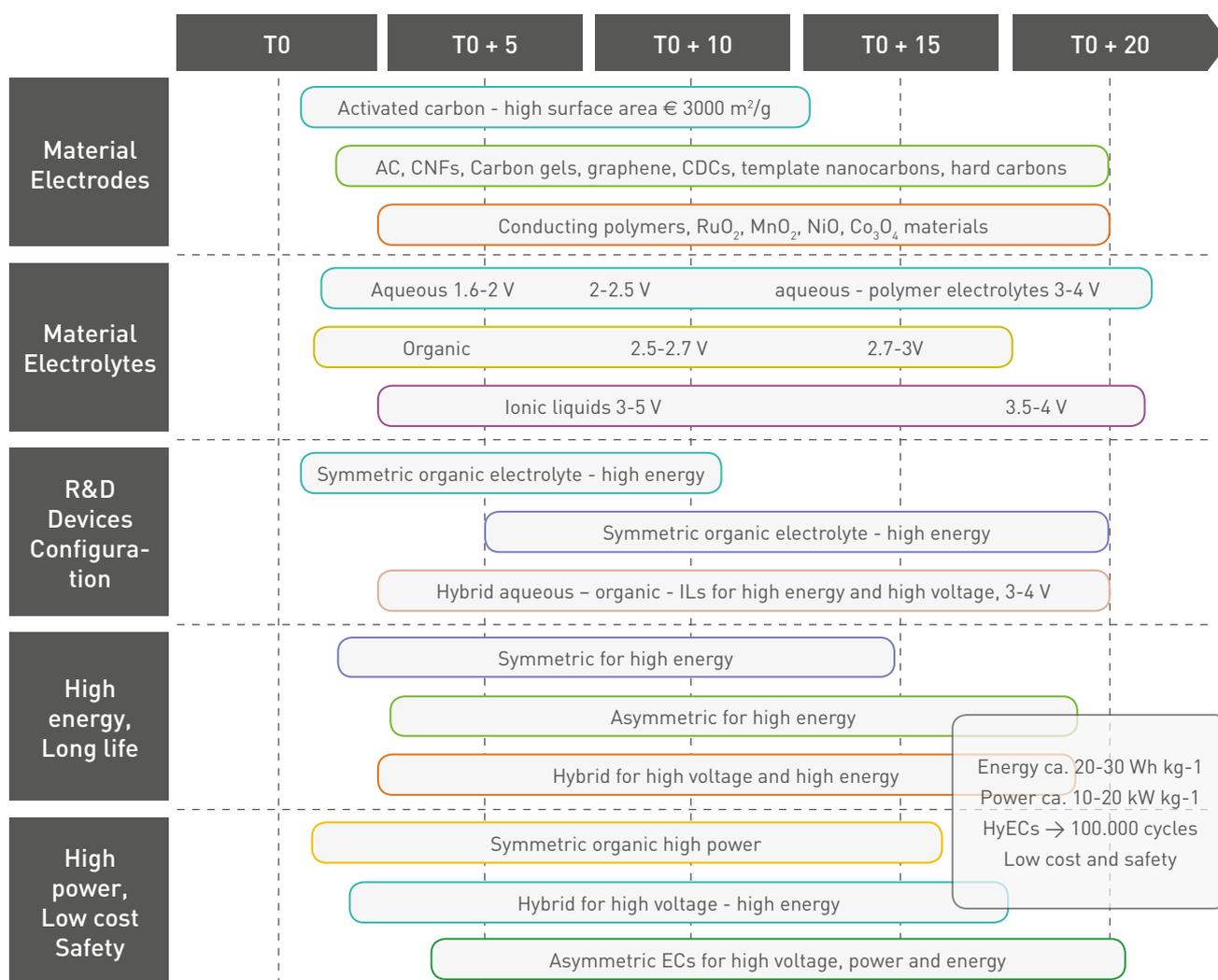


FIGURE 2 - Tentative Roadmap for SCs with vision to 2030 (prepared by CNR-ITAE from ^{20,21,22,23}).

Carbon remains the preferred material for EC electrodes as it is non-reactive in most electrolytes. Carbon can be derived from a variety of materials and its structure is tunable during manufacturing, allowing the designer to control surface area, pore size and pore volume. While the cost of raw carbon may be low, highly purified finished carbon is generally expensive. However, carbon electrodes have the potential to cost less in the future. Carbon nanotubes (CNTs) or fibres (CNFs), fine-tuned microporous carbons and graphene structures are also under investigation as possible EC electrode materials. High surface area electrode materials

(in general nanomaterials) maximise this interface, resulting in larger capacitance.

Resources and infrastructures

A predominantly research-directed effort on new supercapacitive systems is required and an appropriate funding size range of at least 10-15 M€ per year would be necessary to reach significant EC improvements. As indicated this effort is anticipated in research laboratories and European industry is foreseen to contribute with only a minor part.

20 P. Staiti, A. Arenillas, F. Lufrano, J.A. Menendez, J. Power Sources 214 (2012) 137.

21 Q. Gao, et al., Energy Environ. Sci. 5 (2012) 9611.

22 S. Makino, et al., RSC Advances, 2 (2012) 12144.

23 K. Naoi, et al. Energy Environ. Sci., 5 (2012) 9363.

Clustering of research groups in Europe as well as organisation and effective distribution of efforts between electrochemical research centres in Europe is required as an important step stone on the way to consolidating the full benefit of European electrochemical storage potential in the future by integrating and complementing current national and European research programs and projects for optimal utilisation of resources and efforts, as is underway in EERA collaborations. A stronger and more intelligent coordination of resources (central EU resources as well as national resources in member states) will improve the overall outcome to the benefit of the European population: this optimisation process has been started on a voluntary basis in EERA, which are also aiming at integrating resources and infrastructure.

Until now, for grid applications the most common use of SCs in UPS (Uninterruptible Power Systems) has been complemented by a very few demonstration projects. Such (large scale) demonstration projects are recommended.

6.3 Mechanical Energy Storage

Compressed Air Energy Storage

CAES plants are used to store electrical energy. During charging the electrical energy is converted into potential energy of the pressurised air and stored in this form. Turbo, piston or radial compressors can be applied to compress the air. The compressed/pressurised air can be stored in underground caverns or other (above surfaces) pressure vessel. Heat generated during compression can be stored in order to increase the round-trip efficiency. During discharging the air from the cavern or pressure vessel is released and drives the expander of a turbo, piston or radial expander. Before expansion the compressed air must be preheated to avoid freezing of the expander. In case that the heat from compression is used to preheat the air before expansion the process is adiabatic. If external heat input is used to preheat the air by combustion the process is diabatic.

Maturity of technology

However today worldwide only two plants exist, Compressed Air Energy Storage is a relatively mature technology. The 321MW plant in Huntorf (Germany) has been in operation since 1978 and has been stopped and started more than hundred times per year for decades²⁴. The 110MW McIntosh plant in the USA was built in 1991 and is still in operation. Small scale CAES has not yet achieved the same technical maturity as large scale CAES but several companies are developing this technology. First decentralised CAES pilot plants are expected to be commissioned in second half of 2013.

Large-scale CAES has evolved with the development of technologies and is considered to have three generations: i) First generation CAES plants: The first generation system, also known as the conventional CAES system, is the only generation of CAES system in commercial use. Both the Huntorf plant and the McIntosh plant belong to this generation. (ii) Second generation CAES plants: The second generation is in the research and development stage. Most plans are based on the technical improvement and modification to the existing gas turbines, such as CAES with

air injection and CAES with inlet air chilling. (iii) Third generation CAES plants: This concept is also named as Advanced Adiabatic CAES (AA-CAES). The significant benefit of AA-CAES is zero carbon emissions, that is, no combustion process and no fossil fuel consumption in

²⁴ http://www.uni-saarland.de/fak7/fze/AKE_Archiv/AKE2003H/AKE2003H_Vortraege/AKE2003H03c_Crotogino_ea_Huntorf-CAES_CompressedAirEnergyStorage.pdf

the expansion mode. The world first AA-CAES demonstration plant is now under developing, named ADELE project, which started in 2010 and is designed to help provide peak-load electricity from renewable wind energy, with a storage capacity of 360MWh and an electric output of 90MW. The site for this demonstration plant is located at Stassfurt in Saxony-Anhalt in Germany.

In addition, 'over ground' CAES technologies have been in recent years rapidly developing.

Applications

CAES is basically suitable for large to small scale storage applications. Markets are expected in northern Europe close to off-shore wind farms. CAES could be applied to serve off-shore wind farm by balancing generation and demand. In addition CAES can be applied to provide secondary and tertiary balancing power as well as black start capability.

The existing large-scale plant in Europe has been grid-connected for decades and thus grid integration of CAES technology is proven technology. No major challenges can be expected here with regard to the technology. However market integration potential in combination with possible applications and technical requirements could be an issue.

It is expected that the first business cases emerge in the markets described above. However CAES is today not economically viable when only single applications are used to generate revenues. This means that CAES will probably have to act on different markets simultaneously in order to justify the necessary investments.

Other conceivable business cases are small scale site independent CAES in medium voltage grids - potentially interconnected - to serve as VPPs and distribution grid support.

Furthermore decentralised CAES technology could be deployed at difficult accessible places with considerable share of fluctuating renewable electricity generation.

SET Plan targets²⁵ for CAES technologies towards 2030 and beyond

TABLE 12 - SET Plan targets for CAES technologies towards 2030 and beyond

Current performance	Target 2020-2030	Target 2050
Adiabatic (with heat storage; 70% efficiency expected) Diabatic (need extra heat during discharge; 55% efficiency expected) Isothermic (Low capacity & power storages; 70-75% efficiency) Liquefied gas (higher cost for similar efficiency but not geographical dependent) CAES \$300-350/kWh (200-250€/kWh) or Capital Cost €470/kW-€2170/kW (depends on CAES type and sizing)	Advanced adiabatic materials for high T° thermal storage: stable, resistant, cheap, high heat capacity, good conductivity & low degradation Demonstration of huge thermal energy storage with new media and container to resist pressure (>200-300 bars) and thermal stresses (gradients >600°C) Liquefied gas systems capital cost/ demonstration of thermal TES unit cost > \$30 to \$40/kWh (20 to 30€/kWh) depending on storage capacity	50% cost to meet longer-term TES cost goals Costs depend on scale and TES Improving efficiency (>70- 75%)

²⁵ http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

Gaps between targets and present performance

1. Too high investment costs
2. For the time being CAES presents relatively low round trip efficiency. Plants (large scale) in operation achieve between 40 to 54% AC-AC round trip efficiency.
3. Present plants burn natural gas for preheating of the compressed air before expansion and therefore the design is not CO₂ neutral
4. Technology Development for Efficient Air Turbines/Expanders
5. Turbo machinery design for these plants is not “off the shelf” components. Compressor and expander cannot be attached to one shaft which negatively influences the efficiency. Optimised expanders are not available; existing steam turbine solutions are adopted to fit the special thermodynamic specifications of CAES plants.
6. Complete System Analysis and Integration with Grid Operation
7. Cost of Constructing Air Reservoirs
8. Underground Storage Resources

Research needs

- Development of adiabatic technology including intermediate storage of compression heat (technology for adiabatic heat capture)
- Adiabatic components require research to reduce potential losses, and to be proven commercially as an equally flexible asset as diabatic components.
- Geological research for different storage mediums (i.e. aquifer/limestone)
- Development of isobaric caverns requires a deep understanding geological formations and monitoring capabilities. Detailed investigations of potential suitable sites as well as development of measures to guarantee the stability of the caverns.
- Development of components for low temperature adiabatic processes
- The long term impact of underground storage to the environment should be assessed. Also, current large-scale CAES plants require combusting fossil fuels, which will lead to carbon oxide emissions and environmental pollutions. To avoid the involvement of fossil fuel in CAES, some improved CAES concepts are under the research stage, such as Advanced Adiabatic CAES (AA-CAES) plants.
- R&D on alternative/new CAES concepts
 - > LTA - Low Temperature Adiabatic CAES
 - > Compressor and heat capture technology for decentralised low-temperature CAES
 - > Investigation and development of new materials for pressure vessels in decentralised applications
 - > Isothermal compressed air energy storage (ICAES)
 - > Isobaric Adiabatic Compressed Air Energy Storage – Combined Cycle (ISACOST-CC)

Incentives and resources

CAES technology does not need special support or incentives except for technical development to become market ready. However as long as the feed-in tariffs of their potential customers (on-shore and off-shore wind farms and PV parks) are fixed and not depending on market prices for electricity and power quality there is no incentives to apply storage technology for REN generators. This regulatory background absolutely negatively influences on the storage technology development and deployment.

Flywheel energy storage

Kinetic Energy Storage based on Flywheels is considered as a fast energy storage technology with the main characteristics of high power and energy density and the possibility to decouple power and energy in the design stage. Moreover 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, are other important characteristics.

A kinetic energy storage system is composed simply by a flywheel driven by an electrical machine, able to work as a motor or a generator. When the machine (acting as a motor) exerts a positive torque T to a flywheel with moment of inertia J , it increases its rotation speed at a rate T/J , until it reaches maximum velocity, storing a given kinetic energy. At this stage the energy can be maintained constant by just supplying the idle losses in the motor. For releasing the energy, the electrical machine (acting as a generator) applies a negative torque $-T$ to the flywheel, braking at a rate $-(T/J)$ and pumping the energy back to the source to where it is connected.

Maturity of technology

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, many technological aspects need to be improved.

Applications

Some specific applications have been identified as suitable for flywheels utilisation in different areas:

- Transportation, to reduce CO₂ emissions and to increase the efficiency.
 - > Electric and hybrid large automobiles (electric buses)
 - > Light trains and underground transportation
 - > Ferries
- Renewable energy generation, to ensure the grid stability, frequency regulation and voltage support.
 - > Wind energy
 - > Solar photovoltaic energy
 - > Wave energy generation
 - > Smart grids
- Industry applications, to ensure power supply or increase the efficiency
 - > UPS
 - > Cranes and elevators

A deep study of the potential applications could be able to reveal new interesting uses, increasing the industrial market for the companies.

Moreover, recent research studies have demonstrated that the use of flywheels not substituting but completing the operation of conventional technologies, such as batteries, can increase their life-cycle.

SET Plan targets²⁶ for flywheel technology towards 2030 and beyond

TABLE 13 - SET Plan targets for flywheel technology towards 2030 and beyond

Current performance	Target 2020-2030	Target 2050
High cycle life >100000 cycles Ca. 4000\$/kWh or ca 3000€/kWh (1500\$/kW or 1000 €/kW) Small 5kWh/100kW (with HTS) 5kWh/250kW (with INES -Inertial Energy Storage)	Reduced friction, higher rotation speed for higher energy storage (>10kWh) Large systems demonstration with strong materials like composites to resist the centrifugal forces Rotor manufacturing cost reduction <3000 €/kWh	Cost reduction Projected Capital Cost 200 - 500 €/kWh Higher energy storage density >100Wh/kg

Gaps between targets and present performance

The technology gaps have been separated in relation with the different parts of the device:

1. Flywheel disc, especially fibre flywheels. It is desired to get flywheels with a higher energy density at a lower cost by improving the fabrication procedure. Metallic flywheels can also be used in some applications, but the performance required and the power and energy densities provide the specification. The mechanical dependence has been considered as a drawback compared to batteries or ultracapacitors (as examples of fast energy storage) but it is becoming more and more released of maintenance in the case of flywheels.
2. Electrical machines, which drive the flywheels. The machine is related to the system power as well as the flywheel which is responsible for the energy. The machine is also related to how fast the flywheel is able to exchange the energy with the load or the grid.
3. Bearings. Since the system is usually rotating to a very high speed (10,000 rpm) at the same time as supporting a high axial force, conventional bearings are not always suitable to be used. Magnetic bearing is a quiet extended technology for high speed systems but a lot of research is still required to ensure the robustness in flywheels. Superconducting levitation bearings have been developed and successfully and tested. EU and US companies offer their own developments of flywheel based energy storing systems. 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 200h. Improvements in order to get higher reliability of the cryogenics are on the way leading to a competitive system²⁷.
4. Power electronics. The speed range of the flywheel is quite large and the machine has to be able to supply or to absorb a certain amount of power. A power electronic converter is in charge of managing the power behaviour of the system, both towards the machine and the electric grid. Moreover, it is possible to get additional advantages of the use of a power converter since it can be used as STATCOM or any other type of grid support, with a minimum increase of the complexity and cost.
5. Digital control and communications. Digital control provides a powerful platform to achieve a high performance in fast energy storage systems together with power electronics, being able to implement complex control strategies and permitting a high performance drive.
6. Security case or frame. The safety conditions of the flywheel have to be deeply studied and the design of the external case is one of the important issues to work on.

²⁶ http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

²⁷ Boeing Flywheel Energy Storage Technology, George Roe (2012)

Research needs

Solving the gaps implies actions in each area of research previously analysed:

1. Flywheel disc. Study of better materials for fibre flywheels (high density) should be carried out in order to reduce the total cost.
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 to search new machine concepts with less magnets.
3. Bearings. Faster control systems are being developed to improve the bearings response and more efficient actuators are used to increase the performance of the complete system.
4. Power electronics. Increase the added value of the power electronics in an energy storage system, ensuring the robustness and reliability.
5. Digital control and communications. Communication improvements permit to control the system with guarantees of robustness, being able to analyse a lot of variables, maintaining a complete analysis of the application from anywhere, being easily integrated with some other subsystems.
6. Security case or frame. A better knowledge and a more wide experience in prototypes would reduce the cost in security.
7. Demonstration plants to demonstrate the convenience or not of flywheel technology for certain applications

Resources and infrastructure

Research centres together with companies have to work together in the integration of flywheels in facilities where fast energy storage is required to test its reliability.

Hydro Energy Storage

Reservoir and Pumped Hydro energy storage (PHS) are amongst the most efficient and flexible large-scale means of storing energy available today. This proven technology is helping utilities to efficiently balance the grid and to develop their renewable energy portfolios. Reservoir and pumped storage hydro are therefore set to play a key role in enabling countries to meet their ambitious targets to cut greenhouse gas emissions and to build additional clean, renewable energy capacity.

Reservoir hydro is able to reduce or stop production and store water when prices are low, and use this water for production when prices are higher. Pumped storage turbines pump water into an upper reservoir and store it when demand is low. When demand and prices peak, the water is released through turbines to a lower reservoir and the electricity is sold at premium prices. Thanks to their flexibility in power and short response time, further revenue is also derived from the ancillary markets, in which the regulation services provided by hydro power plants and pumped hydro energy storage plants are remunerated.

This allows utilities to get revenues from the storing of variable renewable energy, which might otherwise be lost. Up to 80% of the energy consumed during the overall cycle is recovered, which can be sold when demand peaks.

Maturity of technology

Reservoir hydropower and PHS are mature technologies with many overlapping characteristics and needs. As PHS has some additional aspects being able to use excess energy from the grid, we only discuss PHS in this document in details. PHS holds excellent grid connection properties as illustrated in the following Table 14:

TABLE 14 - Grid connection Pumped Hydro Storage

General Performances	50 to 500 MW <i>200 to 350 MW</i>	Output/Input <i>Most Typical values</i>
	>> 8 hours full load	Storage capacity
	10 to 2000 m. <i>~100 to ~ 600m</i>	Head Range <i>Single stage reversible Francis</i>
	> 80%	Cycle efficiency
Reaction Time	~15 s	50% to 100% Generation
	~ 2 min.	0% to 100% Generation
	~ 5 min.	0% to 100% Pumping
	~ 10 min.	100% Generation to 100% Pumping
Ancillary Services	40% to 100%	Production adjustment range
	70% to 100%	Pumping power adjustment range (Variable speed machines only)
	Reactive power	
	Black start capability	

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 to balance the grid during unplanned outages of other power plants. Thus, PHS plants are already being used for both primary and secondary regulation in the European electricity grid. The technology also enables utilities to operate other energy sources at their most efficient levels, enabling fossil-fired and renewable energy sources to be run optimally.

SET Plan targets²⁸ for hydro energy storage technologies towards 2030 and beyond

TABLE 15 - SET Plan targets for hydro energy storage technologies towards 2030 and beyond

Current performance	Target 2020-2030	Target 2050
GW storage Low cycle cost high capital cost \$500/kW to \$2000/kW (350 to 1500€/kW) Round trip efficiency 70-80%	Materials radical redesign & research on power electronic components Turbine efficiency improvement, etc.	Efficiency improvement / Cost reduction

²⁸ http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

Gaps between needs and present performance

Since PHS is already widely used all over the world on commercial terms the present performance of the technology is already within market terms. However, PHS technology can be improved and provide more and even better business cases.

The way to operate PHS has dramatically changed following the integration of large amount of variable generation. From peak load generation assets operating at maximum power during several hours of the day in order to provide high value energy, the plants now increasingly operate to provide frequency regulation and therefore need to be operated over wider range of power and with as short as possible reaction time. The need for increased flexibility is therefore one key area for development. It means that pump turbines must be optimised to provide wide range of power in generation mode and that variable speed technology needs to be developed further in order to allow the regulation in pumping mode. This latter need will also necessitate developing new concept of pump turbines able to provide the full benefit of regulation in pump mode.

One can also anticipate that the introduction of large HVDC electric highway combined with the development of large quantity generation assets connected through power electronics will bring new needs for ultra-fast regulation. Variable speed technology might allow the PHS units to operate as flywheels and deliver power regulation in milliseconds.

Besides working on further enhancing PHP flexibility, one must also develop solution to reduce the inherent technology limitation that is its dependence on geography. One needs indeed a different elevation between the upper reservoir and lower reservoir. 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 plants concepts.

Equipping very high head (above ~700m) and very low head (below ~100m) sites remains challenging. Current multi-stage reversible pump-turbines (RPTs) used above 1000 m head do not provide power regulation in generating mode as single-stage RPTs our double stage regulated RPTs do. Therefore, very high head pumped storage power plants would require new type of economically viable solutions to provide the much needed flexibility: technologies such as variable speed or multiple stages regulated RPT need further developments.

In low head sites, present problems are different. In generating mode, RPTs are able to provide load-frequency regulation with the help of conventional speed governors. Nevertheless, in low head pumped storage power plants with a wide range of head variation in relative terms, the efficiency of RPTs decreases significantly as the operating conditions separate from rated operating conditions. Variable speed or double regulated turbine (Deriaz or bulb) is a proven means to alleviate this problem. In pumping mode, fixed speed RPTs have a high probability of reaching the stability limit when the range of head variation is significant in relative terms; of course, efficiency also decreases as the operating conditions approach the stability limit. In pumping mode, variable speed would not only be necessary to provide load-frequency regulation but also to guarantee stable and efficient operating conditions.

In the case of low head sites, the above-mentioned problems are critical since their economic feasibility is hardly justifiable in most European electricity markets, only with the net revenues that can be obtained from the arbitrage between peak and off-peak prices. Economic feasibility of high head sites is less difficult to justify, but could be significantly improved if these problems were properly addressed.

From the point of view of the electric power system, this is not only a matter of economic feasibility but of power supply reliability. This problem will gain more and more importance as the amount of non-dispatchable energies increase, as it is foreseen for the next future.

The major gaps between needs and present performance can be summarised as:

1. Local geographic preconditions set restrictions on where PHS can be utilised
2. Flexibility of PHS facilities should be improved
3. Non-technical gaps related to business models, regulatory framework, environmental impacts and social acceptance

Research needs

- Expand possibilities for installation of PHS:
 - › Develop new turbines in order to allow the upgrading of conventional hydro plants into pumped hydro storage while keeping the existing powerhouse (to minimise cost and environmental impact). This will require new pump turbines design since pumps generally require lower foundations.
 - › Develop sea water PHS
 - › Study development of underground reservoirs suitable for PHS in connection with surface reservoirs
 - › Develop new concepts for PHS e.g. by moving solid mass like soil
 - › Minimisation of environmental impacts e.g. by utilising existing reservoirs
 - › Detailed studies of the Energy Island concept (a reservoir in the sea to build a low head PSP) with particular emphasis on economy and underground potentials in Europe. The dikes of the island can be used to install off shore wind mills. This will also necessitates specific very low head equipment developments
 - › Establish smaller demonstration projects for new PSP concept (see e.g. Gravity Power and Bladder reservoirs)
 - › Expand 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
 - › Development of standardised mini/micro cost-competitive PHP applications for centralised and decentralised solutions
 - › Development of standardised hybrid PHP-wind/photovoltaic applications on both a mini and micro scale for centralised and decentralised solutions
- Increase flexibility of PHS by
 - › Developing variable speed motor generators to allow regulation in pumping mode and flywheel operation to provide millisecond power regulation. The technology is very young and needs improvement to reduce cost and technical limitations (speed/power,...)
 - › Exploitation of the synergy between PHS technology and HVDC technology to develop large variable speed solution with power electronics on the stator
 - › Increase the turbine flexibility. Present turbines are able to operate stably between 50/70% and 100% max power. Below this limit high vibration coming from hydraulic “turbulences” occur and they limit turbine lifetime. One needs to improve the turbine hydraulic design, and better understand the fluid-structure interactions. This requires developing simulation models and experimental analyses in order to study phenomena that are not mastered yet.
 - › Increase the stability in the transition between the modes of reversible machine: present reversible pump-turbines present an instability operating zone in the transition between the two modes (s-curve). This requires developing simulation models and experimental analyses in order to study phenomena developing in this transition zone that are not mastered yet.

- › Increase the pump stability at part loads: present reversible pump-turbines present instability at part loads. This requires developing simulation models and experimental analyses in order to study phenomena that are not mastered yet.
- › Shortening start-up and transition times.
- Non-technical issues
 - › Development of business models that include pumped storage hydropower, grid connections and market models for different time-horizons
 - › Development of remuneration systems that compensate flexibility and storage capabilities
 - › Environmental impacts of pumped storage hydropower and necessary grid connections, as well as societal acceptance and siting.

Resources and infrastructure

The following Table 16 shows the estimated R&D needs for the period towards 2030. A more detailed description on estimated R&D need is provided in Annex III.

TABLE 16 - Estimated R&D needs hydro energy storage technologies

Field	Subject	Budget	No. of projects
Flexibility	Large power range Pump turbines	3-10M€	9
	Cycles resistant units	5-10 M€	4
	Fast response units	10 M€	2
	Improved ICT technology: Information, intelligent and interactive	2-10 M€	6
	New Regulation Adaptation	10 M€	1
Geographic limitation reduction	More complex sites to equip	2-1 0M€	11
	Cost-competitive small-scale PHP applications	10 M€	6
	New plant and reservoir concepts	5-10 M€	8
	Upgrade conventional Hydro into PSP	5-10 M€	3
	CO ₂ emission minimisation for PSP equipment manufacturing	10 M€	3
	Environmental impacts in reservoirs used for flexible hydro operations and PHP	20 M€	10
	Regulatory framework and business models PHP at multiple time scales	10 M€	5

For Demo and Pilot test projects it is estimated that each topic (see Annex III) will require budgets in the range up to several hundred M€ with a need for funding of about one third.

6.4 Thermal Energy Storage

Thermal energy storage (TES) is a key element for effective and efficient generation and utilisation of heat where heat supply and heat demand do not match spatially and in time. This covers effective thermal management in the sectors heating and cooling, process heat and power generation as well as increased utilisation of renewable energy systems. A specific feature of thermal storage systems is that they are diversified with respect to temperature, power level and use of heat transfer fluids and that each application is characterised by its specific operation parameters. Thus, availability of a broad portfolio of storage materials and design concepts is needed.

Heat can be stored in a number of ways:

1. **Sensible Heat Storage** results in an increase or decrease of the storage material temperature, stored energy is proportional to the temperature difference of the used materials. Electric storage heating is based on storage of transformed electrical energy as sensible heat in a core of bricks. As required this sensible heat is released into rooms by radiation and convection.
2. **Latent Heat Storage** is connected with a phase transformation of the storage materials (phase change materials - PCM), typically changing their physical phase from solid to liquid and vice versa. The phase change is always coupled with the absorption or release of heat and occurs at a constant temperature. Thus, the heat added or released cannot be sensed and appears to be latent. Stored energy is equivalent to the heat (enthalpy) for melting and freezing.
3. **Thermochemical Heat Storage** is based on reversible thermochemical reactions. The energy is stored in the form of chemical compounds created by an endothermic reaction and it is recovered again by recombining the compounds in an exothermic reaction. The heat stored and released is equivalent to the heat (enthalpy) of reaction.

Maturity of technology chain components

Sensible heat storage is basically a mature technology, since it is commercially available for many years in the form of domestic and industrial hot water and ice storage systems. For Concentrated Solar Power (CSP) the most common heat storage system is based on a two-tank storage molten salt system. Furthermore, electric storage heaters are well-established in the residential area. Underground Thermal Energy Storage (UTES) for low temperature applications (at less than 40 °C) has been demonstrated and it's now available in some European markets, particularly in the Netherlands and Sweden. Currently, very few examples are used for high temperature applications in the process industry. However, the available temperature limitation of water-based storage systems is a serious drawback to make thermal energy storage accessible for seasonal storage, the industrial process heat sector or CHP generation and CSP plants.

Applications

The first new-coming applications for TES systems are expected within the areas of

- Solar heating and cooling of buildings.
- Industrial process heat sector to be used as a heat management tool to increase efficiency and reduce specific energy consumption of industrial manufacturing processes and

- Power generation with thermal conversion processes – combustion engines, steam or gas turbines, ORC etc. – to make conventional power plants more flexible and to support CHP implementation, where heat production can be stored temporarily for subsequent use
- Seasonal heat storage in combination with district heating systems
- Intermediate storage of compression heat in Adiabatic Compressed Air Energy Storage plants
- Large scale solar thermal systems for heating and cooling, process heat and power generation including Concentrated Solar Power
- Heating of residential buildings, whereas a demand side management system allows the use of electric energy from renewable sources for heating with electric storage heaters and / or heat pumps.
- Storage of heat from electric heating elements working as a fast balancing service in the electricity grid.

Economic targets for TES technology towards 2030

- To reduce, in the short to medium term (until 2015), the specific investment cost of latent heat storage and sorption storage for industrial waste heat storage and improved thermal management below 100 €/kWh and to identify niche applications for thermo-chemical storage;
- To have, in the medium to long term (2020), a specific investment cost for compact latent heat and thermo-chemical storage below 50 €/kWh;
- To have, in the long term vision, thermo-chemical storage tanks for solar thermal power plants and industrial process heat applications with operating temperatures over 400 °C to take advantage of a high energy storage density. In the medium term, the goal is to provide efficient energy storage tanks with specific investment costs of about 30 to 40 €/kWh.

Gaps between targets and presence performance

1. Too high investment costs of the total storage system
2. Materials for use as PCM are still too expensive
3. Low energy density of thermal storage systems
4. Low heat conductivity of storage materials
5. Reliability of thermal energy storage systems
6. Too large loss of heat over time
7. Insufficient knowledge about system integration
8. Insufficient knowledge about environmental impacts
9. Insufficient Demand Side Management (DMS) in combination with Electric Storage Heaters.

Research needs

- Research to identify and develop storage materials sensible, latent and thermo-chemical with increased energy density of storage
- Development of advanced heat transfer fluids for thermal electricity storage systems combining heat transfer and heat storage.
- Development of compact heat storage by use of thermo-chemical reactions
- Development of improved UTES including microbiological issues, operation at higher temperature, component selection to prevent scaling and corrosion.
- Optimisation of hydraulics in advanced water stores, reduction of mixing and increased stratification.

- Integration of phase change materials in building element materials.
- Research of large scale solar heating systems within new heat storage technologies e.g. underground storage and thermo-chemical storage
- Develop advanced storage architecture for CSP including single tank solutions, development of solid media storage solutions, develop new salt mixtures with lower freezing point and higher temperature stability
- R&D of multi-functional materials covering storage plus heat transport e.g. micro-encapsulated PCM used as PCM-slurries R&D of filler materials to replace liquids in sensible heat storage e.g. macro encapsulated PCM.
- Improve relevant thermo-physical properties of PCM and thermo-chemical storage materials by use of special additives or by developing composite.
- Identify advanced heat transfer mechanisms for charging and discharging
- Reduce thermal energy losses and energy losses by
 - > Increasing the efficiency of long term heat storage systems with better insulation
 - > Optimising the thermal layering in heat storage tanks
 - > Optimised method for system integration by use of communications and control systems for combination of heat pumps and heat storage tanks or electric storage heaters with the grid and other renewable energy systems
- Study thoroughly potential environmental impacts of new storage technologies
- Simulation models for PCM and thermo-chemical storage based applications to predict their behaviour in certain conditions (heat transfer, fluid dynamics).
- Simulation models of thermal energy storage in combination with residential heating or industrial processes.
- Development on a universal electric storage heater for PV-self consumption and DSM.
- Development of control strategies for integrating heat storage into the Smart Grid.
- Simulation models of electric storage heaters in smart grids in combination of residential heating of buildings.

Resources and infrastructure

Strong support for research in new materials and technologies for heat storage will be required.

Similarly support for system development will be required for the near future, whereas in a longer time perspective market mechanisms (including taxes) should become sufficient to drive business cases for heat storage in parallel with still more volatile electricity prices for consumers.

A reduction of fees/taxes on electricity from renewable sources for electric heating systems is necessary.

6.5 Multi-Functionality Hybrid Energy Storage Systems Incorporating SMES - a potentially future applicable storage technology

Superconducting magnetic energy storage has been of scientific interest for years and still needs a considerable development effort to demonstrate the practical potential. Long term rather basic R&D effort is required, but on the other hand the technology may hold a considerable potential.

In Superconducting Magnetic Energy Storage (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 at high cycle efficiency (>95%), even if the cooling is accounted for. Other key issues are a high robustness and a long lifetime with an almost unlimited number of cycles. Up to now, the cost for the cryogenic infrastructure has prevented a broader utilisation, but new superconductors which can be operated at higher temperatures, now provide the concrete perspective for new engineering designs. Combination of SMES with large scale storage systems, as electrochemical storage systems, can provide the robustness, high-speed, high peak power, high efficiency and high life characteristics for achieving a complete storage system complementing the lower speed response and protecting against sudden power demands. A new multi-functionality hybrid energy storage system, LIQHYSMES, (see Figure below) has been proposed which combines the use of LIQUid HYdrogen (LH₂) with SMES. The LIQHYSMES Storage Unit (LSU)²⁹ as the core element integrates the H₂ liquefaction part, the LH₂ storage tank and the SMES cooled by the LH₂ bath. This allows jointly utilising the cryogenic infrastructure and drastically reducing both the otherwise significant H₂ liquefaction losses and the cost.

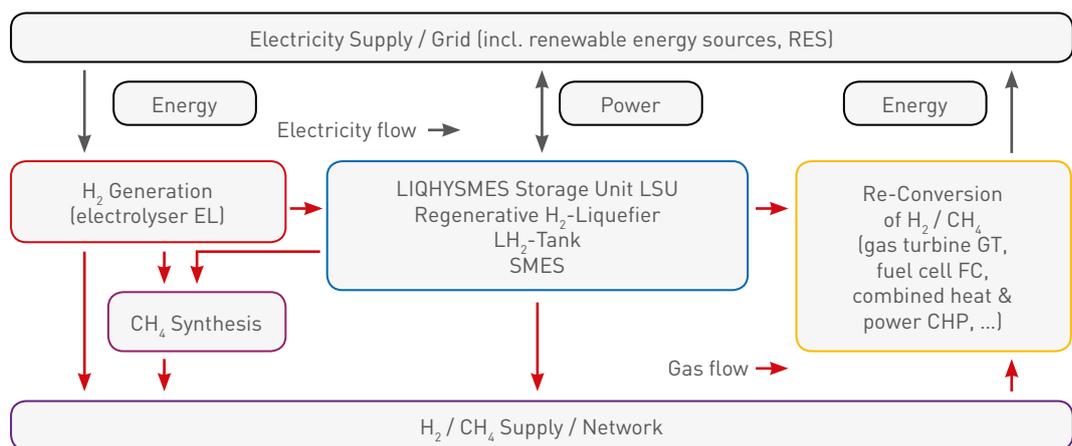


FIGURE 3 - LIQHYSMES Storage Unit (LSU)

²⁹ "LIQHYSMES Storage Unit – hybrid energy storage concept combining liquefied hydrogen with superconducting magnetic energy storage", M. Sander, R. Gehring, H. Neumann, T. Jordan, Int. J. of Hydrogen Energy 37 (2012) 14300

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.

In the following mainly the LIQHYSMES-specific features not addressed in the section on Chemical Energy Storage - Hydrogen, Synthetic Fuels and Chemicals - will be discussed.

Maturity of technology

So far the focus of the research on LIQHYSMES was on various design studies and simulations related to SMES, H₂ liquefaction and the anticipated buffering capabilities of LIQHYSMES model plants. In consonance with the SMES systems developed, the major outcome of these studies is that no critical issue could be identified which would exclude a cost-effective realisation and grid integration of large scale LSUs. First steps towards building a corresponding LSU on a small laboratory scale have been made.

Applications

Since LIQHYSMES plants do not depend on specific geological formations, they can be positioned everywhere, and consequently markets should be addressable everywhere in the world where ambitious plans for fluctuating renewable energy sources (RES) and limitations of the grid infrastructure foster the introduction of large scale chemical energy storage. Highly industrialised regions characterised by a high level of digitisation and particular needs for high quality supply would then particularly benefit from the ancillary services of the SMES.

Potentially attractive locations in the electricity network might be those where the LIQHYSMES plant 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. Potentially attractive locations in a future H₂ supply network might be those where the LIQHYSMES plant can be combined with the production, storage and distribution of H₂.

A broader introduction of the re-electrification of H₂ will become economical only when the contributions of fluctuating RES exceed 50% of the overall electricity generation. First business cases will emerge where different functionalities of LIQHYSMES plants simultaneously provide different benefits i.e. simultaneously serving the mobility sector, ensuring voltage and frequency stabilisation and providing power quality for increasingly digitised societies.

Targets for LIQHYSMES technology towards 2030 and beyond (not yet covered by SET Plan)

TABLE 17 - targets for LIQHYSMES technology towards 2030 and beyond

Current performance of SMES (SET Plan ³²)	Target 2020-2030 for LIQHYSMES Storage Unit (LSU)	Target 2050 for LIQHYSMES Storage Unit (LSU)
Highly efficient >95% For short duration storage (electricity stored in magnetic field) Superconducting coil cooled below its critical temperature	Integration of regenerative H ₂ liquefaction, LH ₂ storage tank and SMES utilising superconductors with higher critical temperature LSU costs of 500-750 €/kW and 2-3 €/kWh based on the SMES power (w/o grid connection, deep discharge cycles > 1 Million) and the LH ₂ energy (w/o electrochemical energy conversion)	Fully modular, standardised components Minimised on-site manufactures / assemblies even for largest systems Cost reduction >10% Flexible positioning and integration in different electrical grid and H ₂ supply infrastructures

Gaps between targets and present performance

Challenges as regarding the SMES are both in the field of new superconducting materials and adapted novel designs & systems essentially based on modularity. The major H₂-related challenge of LIQHYSMES is the development of the regenerative liquefaction process with "cold recovery". Next, the integration of the H₂ liquefaction, H₂ storage and SMES, which reflects the basic synergy, needs to be developed for scalable LSU concepts. Finally, the integration of the LSU in a centralised or virtual plant configuration incl. the grid connection of the H₂ parts as well as the fast modular SMES requires further interdisciplinary attempts.

Research needs

The following fields require R&D efforts:

- Materials issues related to High Temperature Coated Conductors & Magnesium Diboride Superconductors: higher in-field current densities, lower AC / ramping losses, optimised wire architectures, longer lengths of high quality, high amperage conductors and cost reduction³¹.
- SMES-related issues of system technology, integration & up-scaling: loss reduction related to the current feeding & distribution scheme in large systems, new concepts in magnet design and fabrication, standardised components & modular approaches for more degrees of freedom for up-scaling, more detailed application studies.
- LIQHYSMES-related Issues of components & system technology, system integration & up-scaling: loss reduction related to cryogenic components, increase of the liquefaction efficiency due to regenerative liquefaction processes, standardised components and processes for the LSU, electrochemical energy (re-) conversion e.g. of H₂, new power electronics topologies for simultaneously controlling all plant parts & supporting both active as well as re-active power supply, detailed applications studies to identify the techno-economically most promising business cases and corresponding demonstrations of grid-connected LIQHYSMES plants.

Resources and infrastructures

The development of multi-functionality hybrid energy storage systems involves fairly different technologies with a particularly high risk that one of the key components might not meet the economic goals needed for successfully commercialising the complete systems. The remuneration of the benefits of multi-functionality hybrid energy storage systems can only be dealt within the whole framework of new market design for energy storage.

³⁰ http://setis.ec.europa.eu/activities/materials-roadmap/Materials_Roadmap_EN.pdf/view

³¹ "MgB₂: an industrial viewpoint", G. Grasso, S. Berta et al., Workshop on Industrial Applications of Superconductivity, Sestri Levante (Genoa, Italy), October 4-5, 2010



CHAPTER 7

MARKET DESIGN AND POLICY ISSUES

7 MARKET DESIGN AND POLICY ISSUES

The value of energy storage (ES) technologies can only be grasped if one considers its systemic nature. ES technologies must be considered for a given application/service and in a given location in a first hand. On the other hand, it is important to be able to aggregate different applications for the same ES device, in order to increase its economic viability.

The European energy system is designed in such a way, that existing actors cannot capitalise on all benefit that ES delivers to the whole system. They can only access some shares of it due to a.o. unbundling. Therefore market design is a crucial part of the 2030 Roadmap.

In terms of market design this Roadmap commends:

- a legal framework for energy storage at EU level to allow grasping all the added value energy storage can deliver, bearing in mind that the completion of the European single market for energy is crucial. A leeway for national approaches should be incorporated, as long as they do not create market distortion.
- that energy storage constitutes a special and important asset of the complete energy value chain. Therefore the current levy structures (grid fees, taxes or similar) may not hinder or discriminate the integration of energy storage.
- storage devices can render services to the regulated and non-regulated part of the energy system. In providing such services, market based solutions should be preferred whenever possible (grid safety, however, must always take precedence - storage systems are still to be fully integrated into the arsenal of regulatory tools available to System Operators)
- that energy storage gives an added value on different levels in the energy system. Therefore the operator of such devices may differ, as long as this does not trigger market distortion. The market design could also allow specialised storage operators to emerge.
- that potential future capacity markets/payments must be shaped in such a way that without discrimination every energy storage technology should be eligible to participate, if able to fulfil the requirements.
- that specific storage technologies provide capabilities in sector export (e.g. power to gas, electric and fuel cell vehicles, heat storage...). Given the important consequences for the markets involved, we remind that an integrated approach is advisable.
- that adequate financial support for Research, Development and Demonstration must be made available on EU level to allow grasping the full benefit that energy storage technologies can bring to the energy system.



CHAPTER 8

RECOMMENDATIONS AND PROPOSED TIMELINE FOR ACTIVITIES

8 RECOMMENDATIONS AND PROPOSED TIMELINE FOR ACTIVITIES

The transition to a fossil fuel-free European energy system is underway. Political aims based on arguments of economy, security of supply and climate change are expressed and several EU member states have firm plans to reduce fossil dependency to close to zero by the time of 2050.

However it is difficult to predict precisely at which pace the penetration of renewables will approach the desired 100 % or more in terms of installed capacity. Should a linear development be anticipated? Or should rather an exponential or perhaps a logarithmic advancement be expected?

Taking an isolated view at the present European electricity system contours of major balancing problems can already now be envisaged. Wind turbines are being shut down in periods because an overflow of electricity threatens the grid stability. The same problem is reflected in negative electricity market prices: - a price of -200 €/MWh was observed late December in the Scandinavian market on average over one hour. Negative prices are not long-time sustainable but the current presence illustrates the growing balancing problems in the European electricity grid.

Similar problems are seen for solar power installations which have been financially supported widely over Europe in recent years. Solar power is usually grid connected in the low voltage section of the distribution grids and often in individual households. The local grids were not originally dimensioned for the new distributed sources and that gives rise to bottleneck problems as well as problems in maintaining voltage and frequency stably within acceptable limits in the vicinity of the PV installations.

Furthermore fossil power plants are being phased out these years for reasons of emissions and new fossil capacity is not compensating because of uncertainty about investment or for purely political reasons. In both cases the net effect is that the ancillary services provided by central as well as de-central fossil power plants are withdrawn from the market along with the plants themselves.

We believe that the short term electricity balancing market is where energy storage will be first applied based on commercial business cases and we believe the need for additional balancing power will be substantiated already within the next 5 years. However we also find that today only few energy storage applications can justify market-based business cases and this is the reason why many energy storage technologies have not already spread into the market.

Much of the above reasoning puts emphasis on economy in energy storage and it is interesting to note that the cost issue is also pointed out with high priority in the individual technology sections of this roadmap (see section 6) as a general issue in the subsections on “Gaps between targets and current performance” for the technologies.

In a long-term perspective – and this could well be 15-20 years - we have no doubt that energy storage will become an even more significant part of the electricity system. In this time

perspective not only ancillary services but also energy arbitrage based on stored energy will be finding bridgeheads on the shore of the energy market. This will be one consequence of the increasing penetration of renewable supply sources alongside the corresponding withdrawal of fossil, dispatchable generation capacity.

20 years from now we even believe that energy storage applications will link the electricity system closely to its neighbour sectors in the energy system. 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.

The importance of heat storage is often not recognised as it should be. More than 50 % of the final energy demand in the EC is used for generating heat and already now heat storage is utilised in water-based systems for domestic and district heating. In terms of energy heat storage is by far the largest single energy storage application field in Europe. We believe that heat storage technologies will very soon be even more important both for balancing the electricity grids and for better and more economy efficient heat management by the consumers. However, better materials and large scale heat storage technologies will be required to manage waste heat and seasonal variations in heat demand as well as the special case of intermediate heat storage in CAES.

Based on this - and to secure market-ready solutions when required - we recommend:

In a time frame of 2 years

- Start of small to medium scale European demonstration and pilot programs focusing on grid integration of energy storage technologies which possess the relevant maturity. Such programmes will be necessary to secure mature market-ready technologies in the time perspective, where they will be mandatory in the European electricity system. It is important to be aware of the time required for development of the technologies. Technology examples could be chemical storage, grid scale battery storage, new advancements of Pumped Hydro Storage technology in terms of flexibility or development potential and intermediate heat storage for adiabatic compressed air energy storage. Such demonstration projects will in a 5 to 10 years period yield valuable experience on how to design and manufacture dedicated large scale components for future industrial production. Demonstration projects will additionally give experimental evidence for important storage technological properties related to grid integration.
- Activate small (to medium) scale grid-connected battery storage experiments in different places (voltage levels) of the electricity grid for multiple applications and with different technologies.
- Perform large scale underground heat storage studies by modelling storage properties and application potentials.
- Initiate pilot projects for thermal management and industrial waste heat storage.
- Initiating a durable coordinated research effort among leading private companies and research laboratories across Europe within common expertise related to energy storage technologies.
- Encourage modelling efforts able to describe the properties and behaviour of energy storage technologies as well as their contribution to the grid stability or cost reduction for electricity supply
- Support underlying materials and equipment research to allow improving and understanding performance of crucial components and parts in energy storage facilities. Such efforts will have an impact on the economy, performance and flexibility of storage technologies
- Sustain laboratory scale (or equivalent) development and assessment of new, still un-

proven, energy storage ideas and concepts to allow subsequent qualified judgment of their potential and viability for further support and applicability. It is important to maintain such efforts of high risk and to allow new advancements not even perceived today.

- Immediately reinforce education and training programmes of topics of central importance to research and development of energy storage technologies.

In a time frame of 2-5 years

- Design of market terms for integrating energy storage in the electricity market in agreement with the guidelines depicted in section 7 of the present document. Such work should be done in a joint effort between the EU Member States to secure the highest degree of alignment and allow free market operations across Member State borders as far as possible
- Arrange and organise market incentives for integration of energy storage technologies in the electricity grid
- Initiate heat storage experiments (including underground technology) to obtain practical experience for different storage configurations.
- Initiate medium to large scale underground heat storage experiments to obtain practical experience with storage properties in different geological formations.
- Evaluate interaction of gas and electricity grids to the benefit of least cost and least CO₂ emissions from both segments
- Continue basic materials research initiated in the first 2 years period.
- In a time frame of 5-10 years
- Support new large-scale demonstration projects based on the gained experience from first phase projects and including results obtained from materials research and modelling efforts over the (then) past 10 years period.
- Continue basic materials research and evaluation of new ideas.
- Communication and interaction of different storage assets in the grid for supplying ancillary services and load shifting

The above recommendations concentrate the roadmap work in a broad outline. For details the reader should consult the specific technology sections which can be found in the Annex document.

It is important to finally note that the recommendations given in the present Roadmap should not preclude supplementary R&D interest and resources in other technologies that are not presently believed to hold a commercial potential in the 10-20 year period. Technical breakthroughs in other storage technologies may completely change the basis for the present recommendations.

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ABBREVIATIONS AND ACRONYMS

2DS	2 degree scenario
AD	Active Demand
CAES	Compressed Air Energy Storage
DESS	Decentralised Energy Storage Systems
DG	Distributed Generation
DSO	Distribution System Operator
EASE	European Association for Storage of Energy
EC	European Commission
ECs	Electrochemical capacitors
EERA	European Energy Research Alliance
EES	Electrical Energy Storage
ENTSO-E	European Network of Transmission System Operators for Electricity
ES	Energy Storage
EU	European Union
EV	Electrical Vehicle
HV	High Voltage
IEA	International Energy Agency
LIQHYSMES	Long-term energy supply based on liquefied hydrogen
PEM	Polymer Exchange Membranes
PHS	Pumped Hydro Storage
PV	photovoltaic
R&D	Research & Development
RD&D	Research, Development & Demonstration
RES	Renewable Energy Sources
RPTs	Reversible pump-turbines
SET Plan	European Strategic Energy Technology Plan
SMES	Superconducting Magnetic Energy Storage
STATCOM	Static synchronous compensator
TES	Thermal energy storage
TSO	Transmission System Operator
UTES	Underground Thermal Energy Storage
VPP	Virtual Power Plant

