EUROPEAN
COMMISSION

Brussels, 1.2.2017
SWD(2017) 61 final

# COMMISSION STAFF WORKING DOCUMENT

# Energy storage – the role of electricity

# Table of contents

# Energy storage – the role of electricity

## EXECUTIVE SUMMARY

Energy storage is a key component in providing flexibility and supporting renewable energy integration in the energy system. It can balance centralized and distributed electricity generation, while also contributing to energy security. Energy storage will supplement demand response, flexible generation and provide a complement to grid development. Energy storage can also contribute to the decarbonisation of other economic sectors, and support the integration of higher shares of variable renewable energy (variable RES) in transport, buildings or industry. Therefore, energy storage can make an overarching contribution to the implementation of the Energy Union, in particular through its contribution to the internal market and decarbonisation dimensions.

This Staff Working Document outlines the role of energy storage in relation to electricity, presents what technologies and innovative solutions appear more suited for the different purposes and discusses possible policy approaches. Several of these aspects are considered in the framework of the clean energy for all Europeans package. The Market Design Initiative provides a framework for a level playing field for all flexibility solutions in the electricity grid. At the same time the proposed recast Renewable Energy Directive supports energy storage as a mean to integrate renewables, in relation to the right of consumers to produce and self-consume electricity, as well as in relation to renewable fuels of non-biological origin. Furthermore, this document offers a coherent basis for future initiatives and reflections on integration of renewable electricity in other economic sectors.

This document provides an overview of the existing energy storage technologies, which have evolved significantly over the last few years. Currently, pumped hydro storage represents the most mature technology but batteries, compressed air, heat storage and hydrogen contribute with an increasing quantity of services to the electricity grid and to the energy system. The set of services that a storage technology can provide in a defined location determines which solution is most suitable. Several different storage technologies have developed rapidly over the last few years, but further technological progress and cost competitiveness remain essential for large scale deployment. Therefore, the development of storage technologies is an important component of the Strategic Energy Technology Plan and is also identified as a key priority in the Communication on accelerating Clean Energy Innovation.

Subsequently, the document addresses market aspects and regulations that allow energy storage to effectively contribute to the energy system. An increasing quantity of electricity storage could reduce extreme price fluctuations.  EU level harmonisation of the treatment of storage in the energy system would be beneficial, as it would support an EU wide energy market and move towards integration with other energy markets.

The proposed market design initiative introduces a number of elements into the electricity markets which can facilitate investments in energy storage. Investments should be based on market revenue, rather than subsidies, and should be enabled by improved predictability in relation to the contracted services and allow storage facilities to build on the various value streams

that they provide (e.g. ancillary, including balancing services to the grid, avoidance of curtailed variable electricity, decarbonisation of other sectors). Innovative technologies still in development phase would benefit from further efforts to bring these new solutions to the markets, with consideration to the maturity of the technology and relevant state aid rules.

Storage, together with other resources like demand response, should be considered in **grid planning,** both at transmission and distribution level. The **access** to grid connection should be ensured in the same way as for other flexibility solutions by the grid operator. Market, regulatory and administrative barriers to installation and operation of storage facilities should be removed. In the context of participation in the energy markets, a level playing field for storage should be established among storage operations across EU.

Storage operators should be allowed to provide **multiple services** to electricity system operators and also simultaneously participate in other commercial activities with other economic actors (eg. chemical industry). Some specific services provided by storage facilities to the grid operators can be seen as alternatives to grid extension, and this should be reflected in the investment analysis.

Storage services should be traded in competitive markets, where **new flexibility products** would provide a market value reflecting the system benefits of storage. In line with the market design initiative proposal, owners of storage facilities should be **independent** from the grid operators, apart from clearly defined exceptions.

Finally, to allow energy storage to play an effective role in relation to other economic sectors, an integrated approach would be needed. Various mechanisms can support markets for the **integrated solutions**, such as power to gas or liquids, power-to-heat, or integration of variable renewable electricity in mobility or as feedstock in industry (e.g. refining, fertilisers, mobility). Such solutions will support both decarbonisation in various economic sectors and provide additional economic opportunities for energy storage.

# Energy storage - the role of electricity

## 1. The context and challenges for energy storage

In the transition to a low carbon economy, the targets of at least 27% of RES, together with the proposed 30% target on energy efficiency and at least 40% reduction in greenhouse gas emissions by 2030 will be key drivers in achieving the Energy Union policy goals. Moving in this direction implies a higher share of variable renewable energy in electricity generation and further electrification of the energy system. The share of the renewable energy in the electricity sector is expected to increase from 27% today to close to 50% in 2030[1], with large quantities of variable RES. A cost-efficient integration of this amount of variable RES in the energy system will be key to a successful energy transition and economical operation of generation assets.

Energy storage has contributed to the operation of the electricity system already over decades, based on the technical and economic grounds of arbitrage, storing electricity[2] during low electricity demand and releasing it back into the grid during high demand, typically over a daily cycle. Given that in the past the electricity generation mix relied almost exclusively on fossil fuels, nuclear and hydro, and variability of generation was not a major challenge, the necessity for energy storage was more limited and less economically attractive. The global installed capacity in electricity storage was estimated in 2014 in the range of 171 GW[3], approximately 2% of total generation capacities. Further, 16 GW of new storage capacity is announced or under construction globally. The main energy storage technology is pumped hydro storage (PHS), which counts for over 97% of the existing electricity storage capacity.

However, the situation is changing with the growing share of renewables in electricity generation, and this is particularly the case in Europe. It can also be an important element in neighbouring countries with large renewables development potential. In the future system energy storage will supplement demand response, smart grids and flexible generation. The new generation patterns change the requirements on storage facilities. At the same time these changes open up new opportunities to utilise energy storage, by linking electricity sector developments with decarbonisation efforts in industry and transport.

An improved regulatory framework as proposed under the market design initiative (MDI) could contribute to higher efficiency at energy system level, including storage and more efficient use of variable RES. Energy storage could simultaneously reduce the volatility of the electricity prices,

---

[1] European Commission - Fact Sheet, http://europa.eu/rapid/press-release_MEMO-15-5181_en.htm

[2] The reference to energy storage is defined in this document as in the MDI proposal: "Energy storage in the electricity system means the deferring of an amount of the energy that was generated to the moment of use, either as final energy or converted into another energy carrier."

[3] DOE Global Energy Storage Database / Sandia National Laboratories, http://www.energystorageexchange.org/projects , extracted 6 December 2016.

reduce the cost of the electricity system[4] and facilitate a higher share of variable RES in the energy system. The opportunities provided by energy storage are increasingly supported by the momentum in research and innovation making the European economy more competitive.

## 2. Energy storage - relevant energy system developments

The main driver towards larger structural changes in the electricity system is the increasing variable renewable electricity generation. Renewable energy has been supported through policy, and its recent cost reduction brings it towards cost-competitiveness on the energy markets. The cost of renewable technologies have reduced significantly over the last few years[5], with a 80% reduction for solar panels (PV) between 2009-2015, and a 30-40% reduction for wind turbines in the same period. This has already made some RES electricity solutions cost-competitive, and reinforces the credibility of the projections regarding a central role for renewables in the new energy system.

### 2.1 Energy storage supporting the electricity generation profile of variable RES

A good mix of RES electricity (in particular of wind and solar) can in itself already contribute to a balanced operation over certain timeframes. This is becoming important with the growing share of variable RES. The typical **generation profile** of PV has a well-established daily cycle, with a peak around noon and low generation over the darker part of a day. In addition, varying cloud coverage can cause significant changes in electricity generation even over the course of minutes, which presents a specific challenge to the grid. However, the annual variation in PV generation is typically not in line with the annual consumption profile.

The annual profile of wind generation roughly matches the annual consumption profile in some geographical locations, with year-round and higher generation during the winter period. Wind generation fluctuates significantly over longer periods, typically over days or weeks, and needs to be balanced. Energy storage can ensure (i) effective operation of the grid, (ii) fast reaction times in case of rapid power drops or surges, and (iii) linking of various grid elements for a cost-effective balancing of variable RES over various timeframes.

### 2.2 Energy Storage enabling energy efficiency

Both distributed and centralised renewable electricity generation is expected to increase. Consumers will increasingly participate in the energy markets as 'prosumers', i.e. they generate electricity for their own use and rely on the electricity grid for the residual balance. To cope with the challenge of variability from distributed RES, consumers could choose between relying exclusively on the grid or combining grid with local storage solutions. The cost of the grid can be

---

[4] The "cost of the electricity system" refers to the total cost of the electricity system from generation to consumer, including the generation assets, the grid and other necessary equipment, and includes both capital cost and operational cost.

[5] International Renewable Energy Agency (2016), The Power to change: Solar and Wind cost reduction potential to 2025

optimised by using various technologies in addition to the copper cable. Energy storage could contribute to such cost-efficient use of all assets within the electricity system.

Energy **consumption patterns** could change relatively fast, with buildings shifting their energy consumption to electricity (ventilation, heating and cooling) and electromobility becoming more common. The general trend seems to be that there will be an increase in the electricity demand[6], and therefore the electricity system and buildings should be planned taking into account these new consumption patterns and the increasing share of variable RES. This planning should incorporate the use of new and innovative solutions that storage and sectorial integration brings, contributing to **energy efficiency gains at system level** and emission reductions. The transition period towards the new energy system should be seen as an opportunity to optimise the electricity system in line with new needs while adapting the existing grids. The transition will carry initial costs but good planning and innovative solutions in the new energy system will result in lower total cost of the system over time.

Energy storage brings benefits to the electricity system in a similar way as demand response, flexible generation and grid extension (including interconnections): it helps shave the peaks and provides flexibility solutions to market participants. Furthermore, storage can help reduce emissions from the conventional electricity generation: on the one hand by facilitating a more efficient use of the existing assets, on the other hand by reducing the carbon content of the fuels (e.g. blending of the natural gas with renewable hydrogen and synthetic methane).

Using renewable electricity and synthetic fuels in sectors like transport, agriculture or industry, is a viable pathway to decarbonise the energy system in a broader sense. For this **sectorial integration** to happen there is a need to link these different markets. This will bring benefits to the electricity sector, as every step towards the decarbonisation objectives will have an increasing marginal cost if all the flexibility has to be found within the electricity sector itself. Thanks to sectorial integration, some flexibility and storage solutions could come from thermal systems, gas infrastructures, industrial feedstock and agriculture (see Figure 1), while at the same time decarbonising those sectors where alternative carbon-reduction measures could be missing, limited or costly.

---

[6] 1. European Commission (2016), Impact assessment, COM(2016) 861 final: p.24: "Moreover, electricity demand will progressively reflect the increasing electrification of transport and heating. "; p.39: Table indicating increase from 3090 TWh in 2015 to 3397 TWh in 2030.
2. European Commission (2014), A policy framework for climate and energy in the period from 2020 up to 2030, (COM(2014) 15), p.145; "Electricity demand rises 12% between 2010 and 2030, increasing further through 2050 (+32% on 2010).",

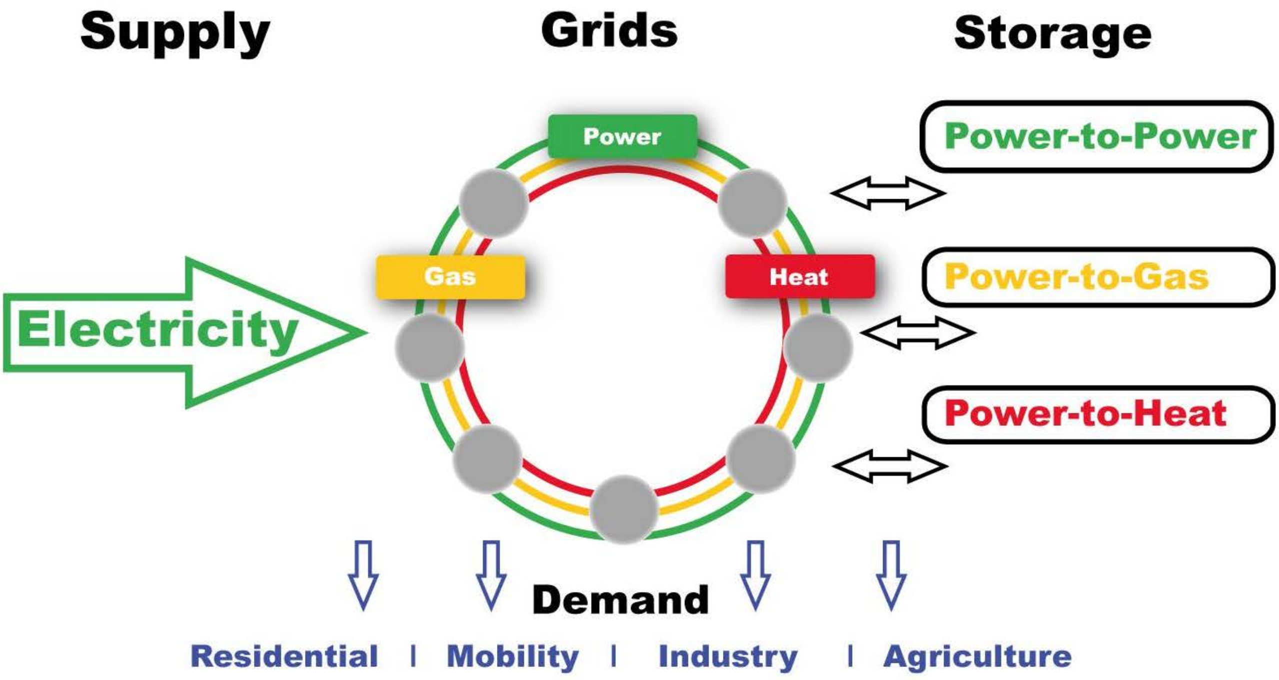


**Figure 1. Illustration of flexibility components in the electricity system.**

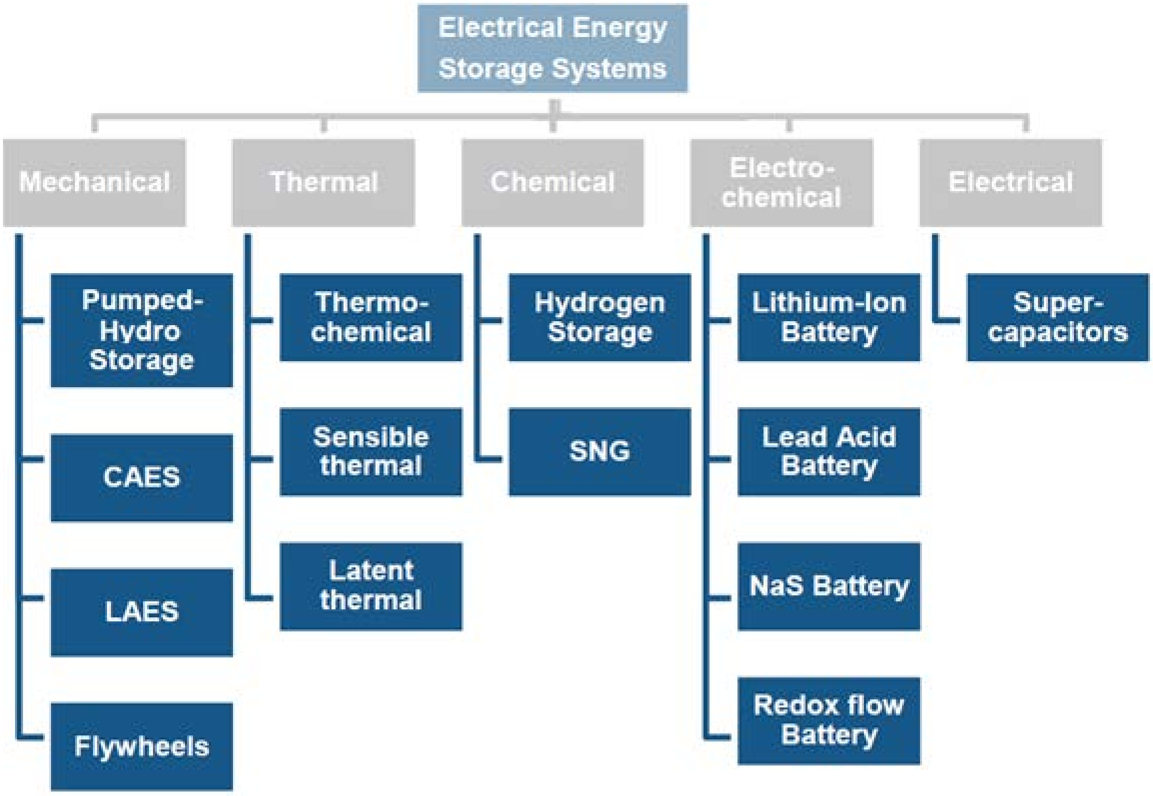
Along with reductions in greenhouse gas (GHG) emissions and increased RES share targets, one of the key objectives within the Energy Union strategy[7] is energy efficiency. "Energy efficiency first" is already applied in EU initiatives at the level of products, industry, transport and buildings. A broader approach regarding resource efficiency, putting together energy efficiency and RES measures, can provide synergies in the integrated operation of electricity, gas and heat networks.

## 3. Energy storage technologies

Energy can be stored using several different technologies: mechanical, thermal, chemical, electrochemical and electrical (see figure 2). The most important functional characteristic of a storage technology is the combination of power and capacity. Together these establish the potential set of suitable applications for a specific storage technology. In addition, the speed of reaction (response time) of a storage technology is an increasingly important factor for the electricity system. These three characteristics, together with efficiency and cost have a direct impact on the business cases through the revenue that the storage can generate on the markets through services and benefits.

---

[7] European Commission (2015), A framework strategy for a resilient energy union with a forward-looking climate change policy, COM(2015) 80



CAES = Compressed Air Energy Storage; LAES = Liquid Air Energy Storage; SNG = Synthetic Natural Gas.

**Figure 2. Example of energy storage types** (source: World Energy Council)

Many methods to store energy exist. A selection of the main energy storage technologies[8] is presented below:

1) Mechanical storage technologies store energy in various forms of kinetic and/or potential energy:

    a) Pumped hydro storage (PHS) is the most mature technology, and accounts for a major share of storage capacity globally (around 97%). The response time for pumped hydro systems varies, with the older facilities having slower response times and the most modern facilities being able to respond within seconds.

    b) Compressed air energy storage (CAES) uses electricity to compress air which is then stored either in underground caverns or above-ground vessels. The stored air is then expanded through turbines to generate electricity again. In adiabatic CAES systems the heat generated during compression is stored to be used at the expansion. The characteristics of CAES are similar to PHS, although CAES is a recent application and only two facilities are currently in operation.

    c) A variant of air-based storage is liquid air energy storage (LAES), which uses electricity to drive an air liquefier to produce liquid air which is then stored in insulated vessels. The stored air is then vaporised and expanded through turbines to generate electricity again.

---

[8] World Energy Council (2016), E-storage: Shifting from cost to value, wind and solar applications

   This technology is currently at the level of pre-commercial demonstration. Viable efficiencies may require coupling with heat or cold applications;

   d) Flywheels store electrical energy as kinetic energy by increasing the rotational speed of a disc rotor on its axis. Flywheels have a very short response time, usually in the order of milliseconds to seconds making them suitable for frequency control.

2) Thermal storages convert electricity to heat, which is then stored in various types of materials. Thermal storages can use resistive heating or heat pumps/engines to convert electrical energy to heat. This heat is then converted back to electricity through steam turbines. Heat could also come from cogeneration plants. Thermal storage can have large capacity and fast response time, while the retrieval response time is similar to the conventional steam turbines:

   a) Thermo-chemical storage uses a chemical which can store heat through changes in its chemical bonds. The initial chemical is heated, which alters the chemical bonds and absorbs the energy in the heat. The chemical can then be "discharged" through a reversed chemical reaction which results in heat. This heat is then used to generate steam for re-electrification. The chemical is typically some kind of salt that can be hydrated.
   b) Sensible thermal storage relies on changing the temperature of a storage medium. This can be water, rock, earth, or anything else that can be heated and which returns a large share of the initial energy when cooled while it generate steam for re-electrification purposes.
   c) Latent thermal storage relies on melting or crystallisation of a material (e.g. paraffin) to store heat. The materials in this application have a higher storage capacity within a small temperature range compared to sensible thermal storage materials.

3) Chemical storage can provide storage services over various timeframes, depending on the specific application. Chemical storage allows cost-effective separation of the power and the energy components in an energy storage application. This allows for easier adaptation to the changing storage needs over time. The characteristics of chemical storage technologies can also support the linking of economic sectors, and the integration of heat, gas and electricity infrastructure. Chemical storage is mostly based on hydrogen production, at least as a first step. The hydrogen produced can be further processed according to the needs of, for example, ammonia, methane or methanol, or other chemicals used in industry. When the hydrogen is further processed to methane, it is commonly called synthetic natural gas (SNG), as methane is the main energy carrying content in natural gas. In such cases, carbon may come from CO2 captured from large combustion plants such as power stations or industrial facilities.

   Modern electrolysers (i.e. units where electricity splits water into hydrogen and oxygen through the process called electrolysis) used for hydrogen production have fast response time and are currently installed in multi-megawatt sizes. The produced hydrogen can be stored in a variety of ways, from small cylinders or tanks to large underground storage facilities. The hydrogen and derived chemicals produced could fuel gas turbines, fuel cells or combustion engines to generate electricity, or used as feedstock in industrial chemical processes.

4) Batteries are a group of electro-chemical storage solutions. Their characteristics depend on the specific battery technology that is applied. Batteries are generally suitable for relatively short duration of storage, and they have in most cases very fast response times (see Figure 3). Batteries are therefore especially suitable for medium or low-voltage distribution networks.

Below the main characteristics of a few different battery types are presented:

a) Lithium-ion (Li-ion) batteries are emerging as one of the fastest growing battery technologies for grid applications. They have significantly benefited from RD&D investment aimed at commercialising their use in the electronics and transport applications. They are presently deployed globally in a variety of applications, from small scale distributed systems (1-10 kilowatt) to large fast-responding systems for frequency services and energy time shifting (1-50 megawatt).

b) Lead-acid batteries are a simple solution, where lead plates are suspended in sulphuric acid electrolyte, which can be charged and discharged. This is one of the cheapest and oldest battery technologies, and is used in, for example, car starter batteries. The competitiveness of lead acid batteries for electricity system purposes is limited by their lower energy density and shorter lifetime compared to other batteries, such as Li-ion batteries.

c) Sodium sulphur (NaS) batteries are deemed to be a commercial technology with several grid applications. This battery is attractive due to its long discharge times, quick response capability and high cycle life. The combination of some safety issues and lack of diversified supply chain has somewhat slowed its global uptake.

d) New chemistries and structures are being researched and developed to reach performance and cost reduction beyond those possible with the above technologies. New chemistries are investigated for electrodes and electrolytes, and further developments include nanostructures and electronics for grid interfaces.

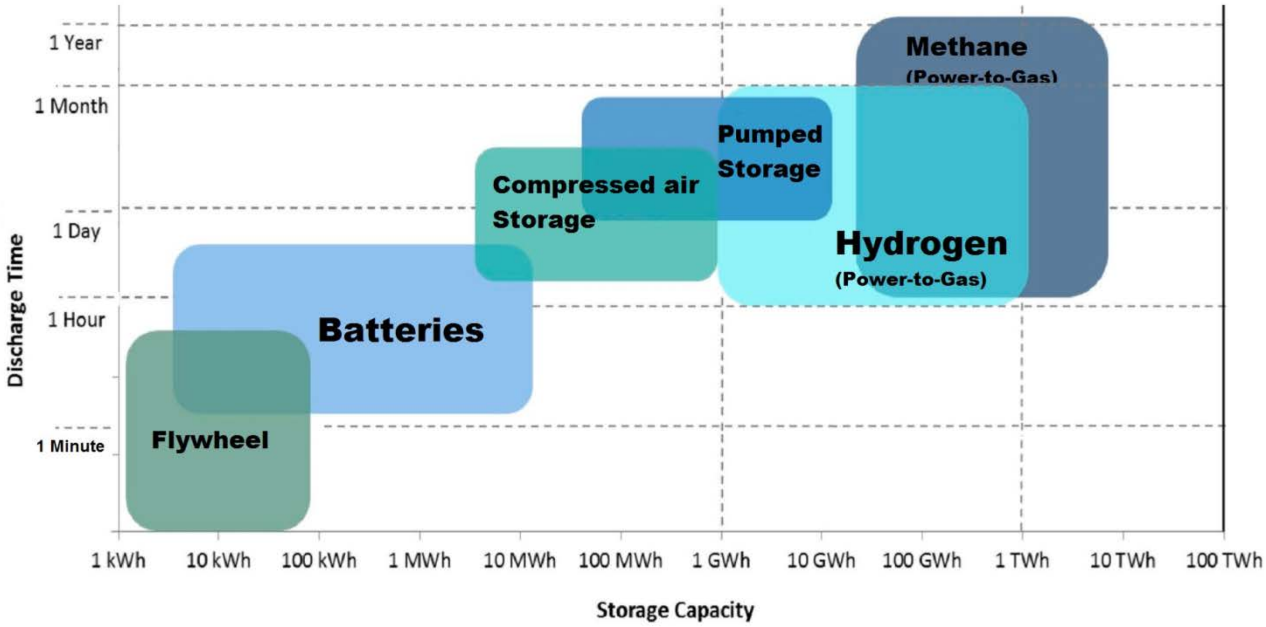
e) A flow battery[9] is a type of rechargeable battery where rechargeability is provided by two chemical components dissolved in liquids contained within the system and most commonly separated by a membrane. Different classes of flow cells (batteries) have been developed, including redox, hybrid and membraneless. The fundamental difference between conventional batteries and flow cells is that energy is stored as the electrode material in conventional batteries but as the electrolyte in flow cells. This battery type has similar characteristics to chemical storage, where the power and energy components can easily be varied separately.

5) Super capacitors are advanced capacitors that have higher energy storage capacity than conventional capacitors, and are able to discharge over longer time periods. They are able to respond very quickly through both charge and discharge cycles, and provide a high power output over a very short response time. This is the only pure electrical storage technology.

   Superconducting electromagnetic storage (SMES) systems store energy in the magnetic field created by the flow of direct current in a superconducting coil. They are used to enhance power quality, but do not currently see widespread use due to cost.

---

[9] Energy Storage Association (ESA) - http://energystorage.org



*Source: School of Engineering, RMIT University (2015)*

**Figure 3. Available storage technologies, their capacity and discharge time.**

## 3.1 Storage characteristics for the market – Capacity, power and response time

The main technical characteristics of a storage facility are capacity, power and response time. Figure 3 illustrates the typical technologies applied depending on the needed storage capacity and discharge time. The minimum discharge time is equal to the capacity divided by maximum power rating. The practical market based application of energy storage highlights also the importance of the location in the electricity grid.

The challenge of the longer time-frame variations also has a direct impact on the choice of storage technologies. Conventional large-scale storage can typically store electricity for some hours. Extending the storage time comes with an decreasing marginal revenue for each additional unit of capacity and time, due to fewer annual cycles for the additional capacity. This limits the profitability of these storage facilities and emphasises the need for a variety of storage solutions along with the existing capacities in the new energy system. A broader range of flexibility products and services will need to be defined and tendered in the market, with particular focus on the extreme requirements: the very short term flexibility and the long term flexibility. Chemical storage and innovative sectorial integration could absorb almost all excess variable RES even in a high variable RES scenario[10] and cover large shares of the longer term flexibility needs in the new electricity system. Meanwhile batteries and even electronics linked to wind and PV are becoming more suitable for the short term needs. Furthermore, several of the storage technologies illustrated in Figure 3 are suited for providing grid services with a response time of seconds (e.g. batteries, CAES, H2, etc.) even if their main application area is usually developed along the indicated discharge time.

---

[10] Fuel Cells and Hydrogen Joint Undertaking (2015), Commercialisation of Energy Storage in Europe. http://www.fch.europa.eu/publications/commercialisation-energy-storage-europe

## 3.2 Storage characteristics for the market – the location

The introduction of new storage solutions into the market brings new possibilities to store energy at different locations and connected at different levels of the electricity grid. Storage facilities can be located with the consumer, with the generator or at the transmission or distribution grid level. The location of storage will impact the business case through market aspects and technology choice. Furthermore, energy storage activity is governed by a specific set of regulations relevant to the location of the storage activity.

Distributed generation can be coupled with distributed storage at consumer level. This allows the consumer to participate more actively in the market and increase the share of consumption of self-produced electricity. Such storage facilities behind the electricity meter will form a part of the consumer's installation.

Centralised storage could be connected to the grid or located close to the generator. It could enable large renewable producers to support their contractual commitments within the electricity market, including any balancing obligation.

## 3.3 The role of innovation and cost of technology

While energy storage has an important potential contribution to the European energy system, further cost decrease and efficiency improvement of storage technologies are needed to strengthen the business case for storage and to support a timely deployment required by the energy transition. Important investment in innovation is needed to pursue the rapid reduction in costs that have been gained over the last 10 years, both for storage technologies and for the related manufacturing technologies. Developing affordable and integrated energy storage solutions is highlighted as a priority to facilitate and enable the transition to a low-carbon energy system based largely on renewables.[11]

Energy storage operators could contribute to a cost-efficient energy system by providing several services, which could also form the business cases for storage applications. In the European Strategic Technology Plan (SET Plan) a key driver is to provide the energy system with the necessary flexibility to incorporate variable renewables. Storage is addressed in a broad sense, including batteries, pumped hydro, power-to-heat, power-to-gas/fuel concepts, etc. and in complement with other flexibility options. The main indicator for the technological development focuses on cost reduction by 2030. The reduction is expected to be in the range of 50% to 70%, depending on the technology.

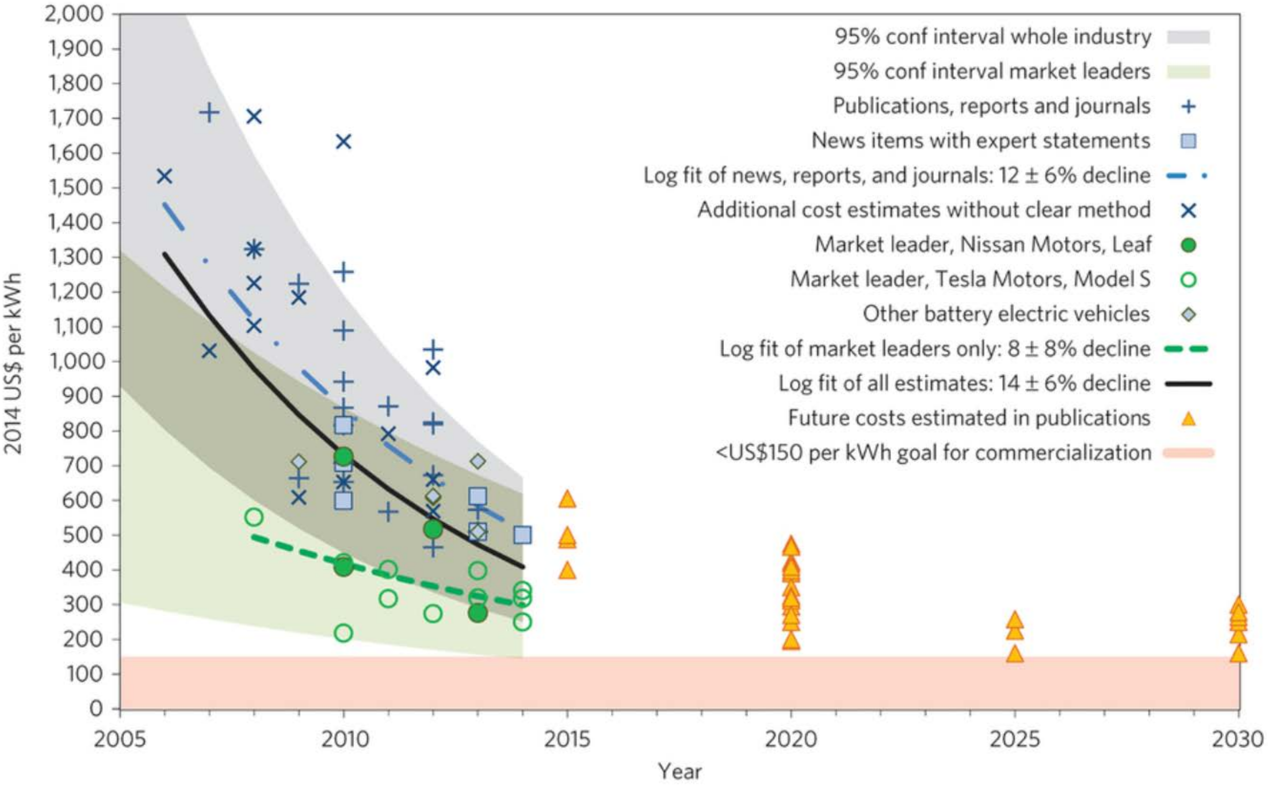
The forecasts of the expected battery cost development indicate that the battery costs are expected to decrease significantly towards 2030. Manufacturing costs are reducing due to innovation and economies of scale. The recent cost reduction is significant, with a drop of 70% from 2007 to 2014[12]. Another reduction of 70% is forecasted towards 2030[13] (graph 1).

---

[11] European Commission (2016), Accelerating Clean Energy Innovation, COM(2016) 763

[12] Björn Nykvist & Måns Nilsson (2015), Rapidly falling costs of battery packs for electric vehicles, *Nature Climate Change* 5,329–332

[13] Fuel Cells and Hydrogen Joint Undertaking (2015), Commercialisation of Energy Storage in Europe

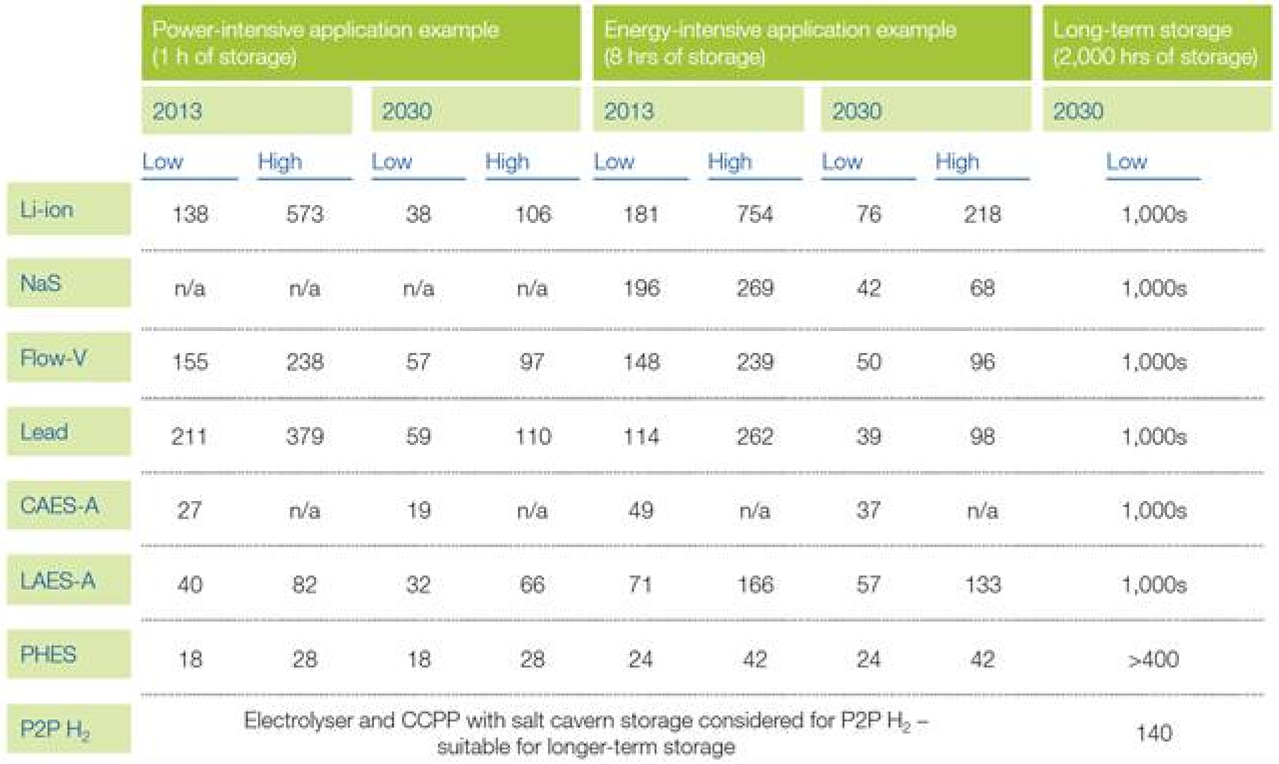


*Source: Nature Climate Change 5, 329–332 (2015)*

**Graph 1. The cost evolution of vehicle batteries.**

The trend of cost reduction is particularly noticeable for some recently developed mature technologies such as Li-ion, NaS and flow batteries (see table 1). New battery chemistries will also improve efficiency and lifecycle.

Under the Integrated SET Plan Action 7, focused on batteries, an all-encompassing research and innovation (R&I) objective aims at developing and demonstrating (i) technologies, (ii) manufacturing processes, (iii) science-based standards and regulations, (iv) increased performance and safety and (v) reduced overall cost of battery systems used for storage purposes in the automotive and other sectors. Detailed targets for costs and performance in both 2020 and 2030 have been specified as scientific targets in the framework of the research and innovation program. For automotive batteries some of the key targets for 2030 are: (i) gravimetric energy density above 250 watt-hours per kilogram (Wh/kg) at pack level, (ii) a battery pack cost of EUR 75 per kilowatt-hour (kWh) and (iii) a battery cell production in EU of 50 GWh/year. For stationary batteries the key targets for 2030 are (i) an energy storage system based on a high-efficiency (>90%) battery with cost below EUR 150/kWh (for a 100kW reference system) and (ii) a lifetime of thousands of cycles. Given the importance of advancements in battery technologies for mobile applications, the EC is prioritising its R&I efforts in this domain.



| | Power-intensive application example (1 h of storage) | | | | Energy-intensive application example (8 hrs of storage) | | | | Long-term storage (2,000 hrs of storage) |
|---|---|---|---|---|---|---|---|---|---|
| | 2013 | | 2030 | | 2013 | | 2030 | | 2030 |
| | Low | High | Low | High | Low | High | Low | High | Low |
| Li-ion | 138 | 573 | 38 | 106 | 181 | 754 | 76 | 218 | 1,000s |
| NaS | n/a | n/a | n/a | n/a | 196 | 269 | 42 | 68 | 1,000s |
| Flow-V | 155 | 238 | 57 | 97 | 148 | 239 | 50 | 96 | 1,000s |
| Lead | 211 | 379 | 59 | 110 | 114 | 262 | 39 | 98 | 1,000s |
| CAES-A | 27 | n/a | 19 | n/a | 49 | n/a | 37 | n/a | 1,000s |
| LAES-A | 40 | 82 | 32 | 66 | 71 | 166 | 57 | 133 | 1,000s |
| PHES | 18 | 28 | 18 | 28 | 24 | 42 | 24 | 42 | >400 |
| P2P $H_2$ | Electrolyser and CCPP with salt cavern storage considered for P2P $H_2$ – suitable for longer-term storage | | | | | | | | 140 |

*Source: Fuel Cells and Hydrogen Joint Undertaking (2015), Commercialisation of Energy Storage in Europe*

**Table 1. The levelised cost of electricity storage for different timeframes (€/MWh).**

Pumped hydro storage (PHS) is the most mature technology and has competitive costs for most of the current storage needs. The availability of adequate additional sites for PHS development is extremely limited, but development of low-head solutions might open up new possibilities. However, only limited improvements are expected over the timeframe presented in table 1. PHS will increasingly be used in conjunction with other storage and flexibility solutions.

Compressed air and liquid air technologies will become cheaper on system level as some of the ongoing development work becomes technically mature. By 2030 compressed air is expected to have a short term storage cost and capacity similar to PHS, but will also be challenged by the lack of available sites to be economically competitive. The best efficiencies for these solutions will be reached when combined with other heating/cooling applications.

Technology improvements and cost reductions in chemical energy storage, mainly in hydrogen, follows significant improvements of electrolyser technologies. At the same time the energy efficiency improvements of fuel cells and conventional (thermal) power generation technologies also contribute to the benefits in the case of re-electrification linked to hydrogen energy storage. The cost of large-scale long-term storage of hydrogen (and related chemicals) is already very low, especially in underground caverns, making it the most cost-efficient technology for long-term storage. This longer storage timeframe reflects also the potential for cost-efficient sectorial integration.

The European Union is financing R&I through the Horizon2020 programme and the EU cohesion policy funds[14] in the period 2014-2020, with close to EUR 100mililon committed to storage projects from Horizon 2020. Energy storage is included amongst the priority actions of the SET plan. The projects address a wide range of technologies from LAES to secondary use of electric vehicle batteries for stationary applications and thermal energy storage. The predecessor to H2020, the Seventh Framework Programme (FP7), funded storage activities with EUR 75million over the period 2007-2013. Funding was provided to one successful demonstration project, the INGRID project storing hydrogen in solid state storage. In addition the Fuel Cells and Hydrogen Joint Undertaking (FCH JU)[15] is also financing hydrogen related energy storage projects out of its EUR 100 million annual budget.

R&I will continue to lower costs and develop new solutions for energy storage, contributing to a competitive advantage for EU. There are various studies estimating the needs, potential and economic benefits for energy storage at the level of a country (e.g. UK) [16] . The European Commission is developing a new energy system model – METIS[17] – able to simulate on an hourly basis the operation of both the energy systems and the energy markets, particularly useful for the planning of more renewable energy as well as the needed storage. Through more analysis on the economics and the markets it will be possible to better postion energy storage in the new energy system.

## 4. Regulatory framework and markets for energy storage

Energy storage has not yet developed its full potential in the energy markets. This is because, on the one hand some of the technologies were not widely developed, and on the other hand the regulatory framework was not in place to accommodate new flexible solutions. Support for electricity generation, regulated prices and green fees have impacted on the development of energy storage. Furthermore, energy storage faced many different regulatory frameworks across Member States, with market inefficiency as a result of this fragmentation. There is no consistency amongst the Member States on the way storage is treated in the energy system. For instance in several countries storage facilities pay grid fees both as consumer and producer, in other countries only as producer, or they have other special regimes. In some cases, by reducing administrative burdens and enabling non-discriminatory grid access for energy storage, the overall cost of the electricity system would be reduced. The new legislative proposals for market design in the context of the Clean energy for all Europeans package[18] support the cost-efficient use of energy storage solutions, covering energy markets aspects, the regulatory framework, system planning and specific technical aspects.

---

[14] Cohesion policy funds are the European Regional Development Fund (ERDF); European Social Fund (ESF); Cohesion Fund (CF).

[15] The Fuel Cells and Hydrogen Joint Undertaking (FCH JU) is a public private partnership supporting research, technological development and demonstration (RTD) activities in fuel cell and hydrogen energy technologies in Europe. The three members of the FCH JU are the European Commission, fuel cell and hydrogen industry grouping and the research community.

[16] Energy Futures Lab, Imperial College London (2012), Strategic Assessment of the Role and Value of Energy Storage in the UK

[17] https://ec.europa.eu/energy/sites/ener/files/documents/overview_metis_v1.2.1.pdf

[18] https://ec.europa.eu/energy/en/news/commission-proposes-new-rules-consumer-centred-clean-energy-transition

So far the option of energy storage has not always been sufficiently considered in the context of electricity **system planning**. The MDI is addressing this issue by especially referring to storage as an element in distribution system planning.

The MDI proposal also comes with a number of more general provisions that would be beneficial for energy storage. Improved cross-border trading and shorter trading timeframes will better reward the flexibility provided by storage. The proposed dynamic pricing contracts should further improve the market for energy storage. Similarly, the right of consumers to produce and consume their own electricity might lead to an increase in demand for storage services and small-scale storage solutions. In addition, the recognition and support of aggregators should encourage a broader and more efficient use of storage facilities. Storage could also possibly benefit from participating in capacity markets and providing decarbonised back-up capacities. These could be achieved in the context of increasing share of renewable electricity, which remain the main driver for energy storage. The improved cost and performance of energy storage should also increase its use for ancillary services and balancing. Furthermore, early storage business cases could possibly be found in the intraday market where trading volumes are much higher and will increase with RES penetration.

## 4.1 Storage within the electricity system

Storage within the electricity system covers all power-to-power solutions, including batteries, pumped hydro and compressed air energy storage. It also covers power-to-hydrogen when the produced hydrogen is used for re-electrification. These storage facilities should operate in the electricity markets on a competitive basis within the regulatory framework provided by the MDI proposal.

The lack of a clear **definition** for energy storage in the regulatory framework resulted lack of coherence in the classification of storage facilities into generation and/or consumption[19] across Member States. This situation is being addressed in the MDI by new proposals and by a new definition: "**Energy storage in the electricity system means the deferring of an amount of the energy that was generated to the moment of use, either as final energy or converted into another energy carrier**."

The grid operators should be allowed to recover the costs associated with the services procured from storage operators if those were necessary for efficient system operation. Furthermore, network fees should provide stability and predictability that allows investments in long-term assets, like storage facilities.

Storage operators should be allowed to provide **multiple services** to system operators, e.g. for distribution system operator (DSO) congestion management or transmission system operator (TSO) balancing. Storage operators should also be allowed to participate in other commercial activities, and to be remunerated for their contribution to decarbonisation of other economic sectors.

The development and operation of storage facilities is promoted in the new MDI as a commercial activity to be performed by market parties other than regulated entities. TSOs and DSOs should

---

[19] stoRE-project report 'European regulatory and market framework eor electricity storage infrastructure", available on www.store-project.eu. (2015)

not own, manage or, operate energy storage facilities.[20] In exceptional cases the system operators could be allowed to invest in a storage facility, under regulatory approval and oversight, if other market parties are not interested in providing specific storage services, following a transparent market procedure. In these cases, the regulatory authorities should regularly reassess the potential interest of market parties to be involved in such activity.

DSOs should be enabled and encouraged to use services from distributed energy resources such as demand response and energy storage, based on market procedures, in order to efficiently operate their networks and avoid costly network expansions. Storage is a relevant option in **grid planning,** both at transmission and distribution level. Large storage projects, above 225 MW, are included in the selection process for the EU's projects of common interest (PCI). Storage and other flexibility measures could potentially also be associated with variable RES producers where clear bottlenecks in the electricity grid need to be addressed.

Access to infrastructure is crucial for any operator wishing to participate in the energy markets. Storage and flexibility solutions should therefore be granted **access** to the grid under non-discriminatory conditions.

The medium and long-term storage solutions, needed for flexibility in a low-carbon energy system, could be better incorporated into the markets with new **standardised market products**. Another important aspect, where storage could provide value, is security of supply. Energy storage could benefit the electricity system by providing synergies for the security of fuel supply, integration of variable RES and reserve/peak capacity generation. Currently, electricity prices do not reflect when and where there is scarcity of electricity supply in the system in a sufficiently precise manner. Removing price caps and regulated prices, as proposed in the MDI, will improve this situation.

At the demand side, **distributed storage** could stabilise the local system, compensating for the variability of RES and potentially operating based on price signals. These distributed storage assets could be used in the markets, including through aggregators. Distributed storage behind the meter could interact with the markets through demand response on retail markets together with other measures. This framework is also proposed to be improved in the MDI.

## 4.2 Storage connected to the electricity system and sectorial integration

Large amounts of fossil fuels are used to produce industrial feedstock like hydrogen, ammonia and methanol. These feedstocks could be produced from variable RES by converting it to hydrogen and potentially further to other chemicals. The variable RES produced hydrogen, and derived chemicals, could also be used in agriculture and transport. These solutions would also promote innovation within European manufacturing industries and contribute to a **European global leadership** within the hydrogen industry, for which a regulatory framework may need to be further developed. There is significant untapped potential to be addressed also within the energy and climate policies.

The industry, agriculture and transport sectors together use much more energy than what is

---

[20] Proposal for a Directive on common rules for the internal market in electricity, COM(2016) 864 final (recast of Directive 2009/72/EC).

transmitted through the electricity grid. These sectors could potentially provide significant additional **flexibility for the electricity grid**. This flexibility could contribute to improved cost-efficiency in the integration of large variable RES. In certain cases this could contribute to improved competitiveness of local industries. As a horizontal measure, a revised EU Emissions Trading System (ETS) with a functioning Market Stability Reserve will also improve the investment signal for low-carbon solutions.

Many of the integrated solutions can be achieved with hydrogen technologies. Hydrogen and its carriers allow for high **geographical flexibility**. Hydrogen can **store** significant quantities of energy in tanks or underground. It can be delivered by pipeline (including blending in natural gas networks) and converted into chemicals (e.g. ammonia, synthetic natural gas or other liquid carriers) which can be used **locally or transported** also by train, ship or road to industries for energy and feedstock use.

Over half of the hydrogen produced in Europe is used in **chemical** processes; 3 million tonnes (Mt) are used in ammonia production, with almost an equal amount used in methanol production and for other uses. In addition around 15 Mt are used in refineries globally. Producing hydrogen and feedstock from variable RES provides obvious **emission reductions,** but it also provides for synergies with energy storage applications, where these additional markets could provide flexibility, while at the same time improve the business cases for large-scale variable RES energy storages. Large-scale underground hydrogen storage, or ammonia storage, could provide for another revenue stream for excess variable RES and decarbonise several sectors, while also contributing to **strategic energy reserves**.

### 4.2.1 Industry and refineries

The industrial use of variable RES feedstock could have a noticeable positive impact for several policy objectives, in particular decarbonisation. However, these innovative solutions were not a viable option until recently.

Many fuels and chemicals used in industry can be replaced with derivatives from renewable sources (e.g. methanol, acids). Sector specific markets can develop where the regulatory framework is adapted to tap the potential of these new low-carbon solutions. Currently, around 95% of the hydrogen used in industry is produced from fossil sources, mainly natural gas and coal, with the corresponding emissions. Conventional hydrogen production processes from fossil fuels are generally considered to be energy efficient and economical, but the use of "green" hydrogen could be an **additional way to decarbonise** these industrial sectors.

Green hydrogen could be of particular use to the refining and chemical industries. It could replace a part of the 15 Mt of hydrogen used globally in refineries and the impact on emissions would be immediate.

### 4.2.2 Ammonia and fertilisers

The fertiliser production is almost exclusively based on fossil sources and amounts to 1.8% of the global consumption of fossil energy. The production of fertilisers is based on hydrogen, which is often produced from natural gas and further processed to ammonia. This ammonia is then either combined with other chemicals as needed by any specific type of soil (mainly Phosphor and Potassium), or used as anhydrous ammonia applied to the fields with simple tank trailers.

The emissions of ammonia production from natural gas are approximately a tonne of CO2 per tonne of ammonia. As with the industrial applications, the hydrogen in this process could be replaced with renewable hydrogen, produced from renewable electricity, effectively decarbonising the fertiliser production and integrating more renewable energy sources into the fertiliser sector. Liquid ammonia is globally a common fertiliser in agriculture since the 1950's, although in Europe the fertilisers are mostly used in solid form. The global ammonia production capacity is estimated at 242 million tonnes in 2016[21], associated with industry estimated emissions of 360 million tons of CO2, reflecting also the hydrogen production from more carbon intensive coal. That is approximately equal to the annual CO2 emission of France.

Using ammonia as an intermediate buffer for renewable energy is feasible, as ammonia can be stored as a liquid; a standard tank of 60,000 m3 contains about 211 GWh of energy, equivalent to the annual production of roughly 30 wind turbines on land[22]. Ammonia can be then used for industrial processes, in fertilisers or burned cleanly for electricity or heat; the burning process releases water and nitrogen, but no CO2 and little or no nitrogen oxides.

### 4.2.3 Electromobility

The electrification of the transport sector could have a significant impact on the electricity system, both as a flexibility solution but also as an additional load. The most relevant grid powered vehicles are the battery electric vehicles, some with a range extender in the form of a combustion engine or of a fuel cell. From the decarbonisation point of view the most relevant are the battery electric vehicles (BEV), plug-in hybrid vehicles (PHV), hybrid vehicles (HEV) and fuel cell electric vehicles (FCEV). BEV's have seen rapid progress in performance, including reduced charging times and increased range. FCEVs are more recent additions to the market, with several manufacturers deploying new models over the 2016-2020 period, but a larger deployment will depend on the availability of refuelling infrastructure. The market success of cars with an electric drivetrain depends also on national decarbonisation strategies.

The electric vehicles can provide flexibility to the grid and function as distributed storage as well as generators through vehicle-to-grid services. The BEVs and FCEVs have different interactions towards the electricity system, providing different sets of benefits.

A BEV is similar to a stationary battery as regards the electricity system, potentially contributing to the grid services, but with higher uncertainty concerning the availability and state of charge at any

---

[21] International Chemical Information Service, http://www.icis.com/resources/news/2015/12/28/9956097/outlook-16-global-fertilizer-demand-set-to-rebound-in-2016-ifa/

[22] Stichting Public Private Partnership-ISPT, http://www.ispt.eu/

time. The cost of BEVs has reduced significantly over the last few years, due to increased production numbers and reduced battery manufacturing costs. The used batteries from electrified drivetrains could also be used for energy storage purposes after the end of use in the transport sector.

Some Member States and stakeholders are committed to investing in the increase of the necessary refuelling infrastructure for hydrogen. The FCEVs are fuelled with hydrogen, which acts as a buffer between the vehicle use and the electricity system. This allows the vehicle to be used and refuelled without direct (adverse) impact on the electricity system. The hydrogen generation is constantly connected to the grid and can provide flexibility at any time. The FCEV related refuelling infrastructure could provide flexibility to the electricity system, as the refuelling stations would store the energy in the form of gas and also absorb excess variable RES generation. As a direct consequence, refuelling would not necessarily have an immediate impact on the electricity system. The cost of FCEVs has reduced significantly over the last few years, as the technology and supply chain is forming for the manufacturers, who have already decided to start production.

### 4.2.4 Thermal storage

Heating and cooling consume almost half of the EU's energy and a large amount of heat is not efficiently used. Furthermore, large amounts of thermal energy are produced as by-product of other energy uses, and is often not captured and used. The progress towards higher energy efficiency in industries and buildings could increase the use of electricity in heating or cooling, including with heat pumps and in district heating systems. The thermal equipment could provide flexibility to the electricity system grid, when designed to do so, and is often a cost-efficient form of flexibility over a few hours or a day.

Existing electrical heating and cooling applications could in many cases react to the price signals from the electricity markets, while in new and renovated buildings efficient thermal solutions could be beneficial. Thermal storages could be operated in the electricity market through demand response applications. Thermal storage is currently used in industrial applications, where justified by the electricity price signals. In buildings it could be considered as a flexibility measure. At the same time, the use of a renewable heating and cooling could make an important contribution to decarbonising future buildings. The energy efficiency and energy system impact should be reflected in the evaluation of the overall benefits. Their impact should also be reflected in relation to the impact on generation capacity requirements.

### 4.2.5 Storage in hydrogen

Large amounts of variable RES can be stored in the form of gas (hydrogen and other synthetic gases) with various power-to-gas (P2G) technologies, capable of providing significant flexibility to the electricity system and decarbonising other sectors. Hydrogen could be stored at a low cost in for example salt caverns in very large amounts. It could subsequently be used for transport, industrial purposes, re-electrification or injected into natural gas networks. The underground storage technology is already proven, for example, by a large hydrogen underground storage operating since 1980's in Texas and supplying 50 refineries and chemical plants in the area through a 500km pipeline. These underground storages have a total size of[23] 30 million $Nm^3$ of hydrogen. One 0.5 million $m^3$ underground hydrogen cavern could store at higher pressure an energy content of 167 GWh[24]. In comparison, the total global electricity storage capacity is around 500 GWh, including all technologies (mainly pumped hydro, batteries, etc.). Hydrogen could also be synthesised to methane, which would enable storage in existing natural gas storages. The potential is significant, as the underground storage sites for methane (natural gas) in Europe (EU-28) have a capacity of approximately 1200 TWh[25], while the annual electricity generation from all sources in 2014 was around 3000 TWh[26]. In addition, the power-to-gas conversion could exploit the possibility to use the already developed natural gas infrastructure for long-distance transport.

Hydrogen can be blended in the natural gas infrastructure up to a certain percentage (between 5-20% by volume, as demonstrated by the EC research project NaturalHy). Work is going on in the technical standards organisation CEN/CENELEC, both on the content limits and on the technical aspects at the points of injection. Subsequently the relevant regulations on gas quality and limits of hydrogen at EU level could define safe levels of hydrogen in the natural gas infrastructure and enable the transfer of the low-carbon value of variable RES between the electricity networks and the gas networks.

# 5. The way forward for energy storage

The value brought by energy storage to the energy system is well recognized, and its deployment is expected to be driven primarily by private investments. A number of market imperfections present in the current energy markets are being addressed in the proposed MDI to enable such investments to take place. In addition, innovation and market introduction of new technologies may also need specific support to validate and accelerate the integration of appropriate technologies and business models.

A number of research and demonstration projects are financed from R&D budgets at European and at national level. Market introduction of low-carbon technologies is supported e.g. by the InnovFin EDP scheme[27]. Further financing for more mature storage technologies is available through the European Structural and Investment Funds, Connecting Europe Facility and European Fund for Strategic Investments. To enable market-based financing for a wider market uptake, the energy markets will be improved to remunerate flexibility for its value, in line with the market design proposals.

## 5.1 Principles supporting the market development for energy storage

Energy storage can combine various value streams, contributing to the new energy system. This requires the development of new business models both in relation to the electricity system and to

---

[23] Oak Ridge National Laboratory, www.ornl.gov

[24] "Underground salt caverns of 500,000 m3 at 200 bar corresponds to a storage capacity of 167 GWh hydrogen.", http://energystorage.org/energy-storage/technologies/hydrogen-energy-storage

[25] http://www.gie.eu/index.php/maps-data/gse-storage-map

[26] http://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_production,_consumption_and_market_overview

[27] Innovfin Energy Demo Projects financing scheme operated by the European Investment Bank. http://www.eib.org/products/blending/innovfin/products/energy-demo-projects.htm

sectorial integration. The following four principles, consistent with the proposals in the MDI can serve as a basis in this process:

- **Energy storage should be allowed to participate fully in electricity markets**

Energy storage can be developed at consumer or grid level, or even by an electricity generator. In all cases the decision to invest (by a household, a wind farm or a service provider) is based on (i) a comparison with alternative investments, or no investments and (ii) higher exposure to scarcity prices or other supply risks. Investors will make their decision based on the economic and technical analysis.

Studies show that an electricity system with a large share of variable RES appears to be more cost-efficient with storage than without storage.[28] That is even more apparent in an island system with high share of variable RES. However, before investment decisions in energy storage can materialise, a policy and regulatory framework needs to be in place, enabling flexible mechanisms to play their role in making the energy system more sustainable and more competitive. The basis for such a framework is proposed in the Clean energy for all Europeans package.

The traditional function of energy storage was to absorb energy during periods of excess generation or low prices in order to release it back to the electricity system in times of scarcity or high prices. The usage of storage for this basic function provided benefits which enabled a business case. However, the requirement for flexibility, in terms of quantity and time frame, is significantly different in the new low-carbon energy system. The market design proposals will help to put a real value on flexibility, including from energy storage, in the electricity system. Strengthening the link between the electricity system and the decarbonisation of other economic sectors (e.g. mobility, industry) could also reduce the overall energy system costs.

- **Energy storage should participate and be rewarded for services provided on equal footing to providers of flexibility services (demand response, flexible generation and adaptation of transmission/distribution infrastructure)**

More flexible components will be needed in the electricity system to compensate for the increasing amount of variable RES electricity generation. Storage is one of these components and its benefits should be recognised in markets, so as to allow equal treatment in relation to the grid operation. This issue is reflected in the level playing field presented in the MDI. The MDI refers specifically to storage facilities linked directly and providing services to the electricity system. Additionally, where storage provides services that go beyond the conventional flexibility solutions, such as decarbonisation of other economic sectors, this can contribute to its business case.

Of course, any reward schemes and incentives for storage solutions developers/operators should be designed and implemented in compliance with competition law (including State aid) and sector-specific regulations.

---

[28] Carbon Trust (2016), Can storage help reduce the cost of a future UK electricity system?: "…the UK electricity system could reach annual cost saving of up to £7 billion in 2030 with storage in a "Market-driven Approach".

- **Energy storage as an enabler of higher amount of variable RESs could contribute to energy security and decarbonisation of the electricity system or of other economic sectors**

Sectorial integration could provide for further flexibility that would enable a better integration of RES in the electricity system at lower cost than electricity-only solutions. Variable RES generation introduces the need to balance generation fluctuation over longer periods. Energy storage can absorb excess low-carbon electricity and ensure system stability over longer periods.

Variable RES generation introduces the need to balance generation fluctuation over longer periods. Energy storage can make use of the available low-carbon electricity and ensure system stability over longer periods. The physical limitation of common storage technologies (pumped hydro storage, batteries and compressed air energy storage) implies that the marginal cost of capacity becomes too high or the physical storage capacity cannot be expanded sufficiently to satisfy long-term energy storage needs. These concerns can be addressed by integrating several sectors and using chemical storage. Chemical storage could ensure the stability of the electricity system over longer periods,[29] similar to what natural gas storages and gas power plants have done historically. New markets and products would help to create a business case for large scale storage facilities capable of storing and absorbing large amounts of energy over longer timeframes, over several hours or days.

The value of integrating variable RES into the mobility sector is potentially composed of several revenue streams: (i) reducing $CO_2$ emissions, (ii) providing services to the electricity system, (iii) improving energy efficiency and security and (iv) improving the competitiveness of the car industry. Some of these aspects already have a direct or indirect market value. While the market recognises the benefits of battery electric vehicles, fuel cell vehicles and the use of bio based fuels, the use of variable RES in refineries for fuel production is gradually becoming a relevant issue to be addressed on equal footing.

The use of variable RES as feedstock provides potential for further decarbonisation of the economy (e.g. industry), while providing electricity system services and benefits. These additional benefits include the value of shifting to indigenous sources of feedstock (e.g. green hydrogen in refineries) and potentially improving competitiveness of the sector through a low-carbon advantage.

A stronger carbon price signal as well as other supportive policies to reduce emissions in the non-trading sectors will help to promote such solutions.

- **The cost-efficient use of decentralised storage and its integration into the system should be enabled in a non-discriminatory way by the regulatory framework**

Storage facilities placed at the generation or at the consumer could alleviate the pressure on the grid, increasing the stability of the supply and demand at the point of generation/consumption. The value that storage can provide for the integration of variable RES into the energy system should be reflected and rewarded for centralised and decentralised storage solutions alike. Increased scope of balancing responsibility , scarcity pricing and dynamic price supply contracts as

---

[29] Fraunhofer ISE (2016), Lithium-ion batteries: advances and applications. http://dx.doi.org/10.1016/B978-0-444-59513-3.00013-3

proposed in the MDI can help in this sense, as can the use of appropriately structured network charges. In addition, where specific support is provided for example for a consumer installing a PV system, this can be designed to incentivise the consumer to install a battery at the same time, subject to considerations of overall system efficiency.

## 5.2 Final remarks

Innovation and development of energy storage technologies have produced significant cost reductions and performance improvements, especially in batteries and power-to-gas technologies. This progress has increased the possible areas where energy storage can be applied at the same time as there is an increase in the needs for various services in the electricity system. Energy storage technologies could therefore provide alternatives to conventional solutions, and could help achieve the Energy Union's objectives.

The cost of the energy storage systems, their reliability and functionality can be tackled by research and innovation in terms of improved materials and technology demonstration with utility scale field tests. Further progress will require even greater research and innovation efforts and identification of new solutions.

The market environment is rapidly changing with the increased variable electricity in the energy system and the increasing deployment of a number of emerging energy technologies. Energy storage provides benefits through flexibility and through the possibility of better linking of various energy and economic sectors. It also provides benefits in terms of energy security.

The proposals in the MDI and in the Renewables Directive will help energy storage integrate more effectively into the energy system. The recognition of the benefits and complexity of energy storage solutions indicates a promising path towards an integrated low-carbon energy system.