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Topic 8

Electricity Storage: How to Facilitate its Deployment and Operation in the EU

Final Report
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Executive summary

The future electricity system will face various challenges originating from both supply and demand side. Adaptations in system architecture are required to allow for decarbonization while ensuring stability and reliability of the system. Many claim today that larger variability and intermittency of supply must inevitably be accompanied by a significant development of electricity storage. This explains the ever growing attention that electricity storage starts to receive recently from utilities, transmission and distribution system operators, manufacturers, researchers and policy makers. However, electricity storage technologies are only one possible type of means, amongst others like flexible generation and demand side management, to provide various services (such as capacity firming, voltage and frequency control, back-up capacity, or inter-temporal arbitrage) to the system.

To face up with the challenges of the future power system, a comprehensive approach to assess how to enable the development and deployment of electricity storage (and in the broader sense also of other flexibility means) has to be developed. This report analyzes whether the benefits that electricity storage can provide are already recognized and valorized by the existing market design and regulation. First, the drivers for electricity storage deployment in power systems are investigated and it is asked whether electricity storage is a special class of assets for the future power system that should be supported by some particular market design or regulation. Second, evidence is collected on which conditions have led to a more ambitious development and use of storage in selected non-European countries. Third, a systematic approach to identify viable business models in the European power system is provided. Finally, it is discussed whether current market rule setting and regulation allow these business models.

Chapter 2 asks whether alternative means of flexibility – including a more flexible operation of conventional generating units as well as various demand side measures – are fundamentally different. In fact, all are able to (a) react to system requirements of up-/downward adjustment and also (b) include the opportunity to benefit from inter-temporal arbitrage. Dissimilarities come from the form of energy in the conversion and accumulation processes and from operating parameters such as response time, power rating, and energy rating. Therefore, one flexibility means is not necessarily always superior to another. The often expressed need for electricity storage to enable decarbonization rather is a technical and economic question.

The value of storage needs to be assessed under a double uncertainty: There is uncertainty concerning the direction and timing of innovations in storage technologies themselves, but there is also uncertainty concerning the pace of change in generation, demand and grid flexibility. Technology choice and scale will depend on whether we move towards 'European-wide energy superhighways' or whether we move instead towards a system of rising local energy autonomy, featured also by widespread demand side management, which probably would substantially reduce the need for centralized storage solutions.

Beginning with an overview on alternative storage technologies and their deployment, **Chapter 3** then discusses conditions that have led to a more ambitious development and use of electricity storage in the US and Japan. Reasons originate from individual industry structures, strong public support to innovation, but also from specific rules in market design and regulation facilitating the participation of storage in ancillary service markets. To assist the EC in deciding how to most effectively use RD&D to the benefit of the European citizens, the report provides a review of on-going R&D activities of different storage technologies as well as a survey of manufacturers showing the EU's relative position in this specific industry. The chapter concludes with guidelines for the design of public support to RD&D. The importance of EU involvement in direct public support to innovation is confirmed. EU institutions should take an active role in (a) improving coordination among Member State and EU support policies – public support should focus on a balanced portfolio of identified key technologies, and in (b) improving communication and information exchange, for instance regarding functioning practice of 'real-world' pilot and demonstration projects.

Chapter 4 investigates viable business models for electricity storage in the future power system. The core of a business model for electricity storage is how to best match storage facility's functionalities (regarding up- and downward adjustment and accumulation) with the services to be provided. Numerous studies have shown that by focusing on only one specific usage, electricity storage typically cannot reach profitability in the current market context. Today's challenge is how to aggregate multiple services and maximize multi-income streams. In this regards, business models can be categorized by the nature of the main target service, distinguishing between a deregulated-driven business model (major part of income originates from activities in electricity markets), and a regulated-driven business model (major part of income originates from offering services of which a regulated actor is the only buyer). It is discussed how to coordinate the provision of multiple services related to ownership, priority of usage, allocation of capacity, contracting, etc.

Chapter 5 investigates whether current market rule setting and regulation allow these business models to evolve and, thus, whether the services which electricity storage could provide to the system or individual stakeholders are adequately recognized and rewarded. Our analysis reveals that there is room for improving market price signals. First, balancing market rules such as minimum bidding requirements and symmetric up- and downwards bids should be relaxed to allow small, decentralized market players (including storage operators) to participate in these markets. Second, heterogeneous national practices regarding peak-load arrangements need to be tackled to ensure a level-playing field for all flexibility means across Europe. Third, one difficulty for assessing the global value of an investment in storage is the lack of data to estimate future revenues from providing ancillary services. The use of competitive tendering instead of bilateral contracts wherever possible could help to reveal and quantify this value. In the conception of tendering, performance-based, source-neutral remuneration schemes should be adopted.

A proactive regulatory intervention could be helpful in several areas to allow the emergence of new business models. This includes for instance the promotion of market access for aggregators which would allow for the participation of small-scale electricity storage in energy-, balancing-, and ancillary service markets, or defining rules for electricity storage's responsibility to bear the cost of the grid without penalizing its business model. It is important to note, though, that it is beyond the scope of this report to advocate any particular position regarding possible policy options. This would require a careful assessment of which policies would be optimal from a societal perspective, taking into consideration also the impact of heterogeneous national approaches on competition.

The chapter closes with considerations regarding a renewed EU involvement. The future role of the EU mainly relates to ensuring a level-playing field made of well-functioning markets and efficient regulation by establishing best practices in the areas that have been identified above. However, current heterogeneities in national market design and regulatory frameworks applied to storage could impose distortions in competition, and thus, should be the main focus of EU involvement. Amongst others, the report calls for a harmonized balancing market to allow the flexible sources to be used more efficiently on a larger scale. The negative effects of heterogeneity in national balancing mechanisms on competition and the completion of the internal market should be recognized in the Framework Guideline on Electricity Balancing to be scoped by ACER this year.

Introduction

In order to meet European Union (EU) climate and energy policy targets, the energy sector must undergo substantial structural changes in the coming decades. Electricity will play a crucial role in this transformation process, increasing its share of final energy consumption and providing a decisive contribution to the decarbonization of transport as well as heating and cooling services (EC, 2011). The future electricity system will also face various well-known challenges such as an increase in variability and intermittency of generation and the proliferation of distributed energy/power resources like distributed generation, controllable demand and electric vehicles. There is a trend towards smart grids supplying smart appliances and enabling active demand response. An important and growing interplay between transmission and distribution levels will be crucial.

Some stakeholders claim today that larger variability and intermittency of supply must inevitably go with a significant development of electricity storage. This explains the ever growing attention that electricity storage starts to receive recently from utilities, transmission and distribution system operators, manufacturers, researchers and policy makers. The European Association for Storage of Energy was established in 2011. Conferences and workshops all over Europe are organized at least monthly, and various recent academic papers and reports discuss the future role of electricity storage as one key technology enabling decarbonization (see e.g. EAC, 2008; Kaplan, 2009; EPRI, 2010; Eyer and Corey, 2010).

What the future power system needs is not electricity storage as such, but rather a well-adapted system architecture allowing for the decarbonization of the economy while ensuring at the same time system reliability, efficient prices and security of supply. Electricity storage should be considered as one of the many manners to provide various services to the system, such as capacity firming, capacity accommodation, voltage and frequency regulation, or back-up capacity. Therefore, before claiming categorically that more storage should be introduced, it is important to have a comprehensive understanding of the eventual functions that electricity storage has to fulfill, together with other grid-, generation-, and demand side assets of the power system. Furthermore, electricity storage needs to be seen in the broader EU energy context, taking into account possible interactions between different types of energy storage.

Assuming the need for specific storage facilities, the search for workable business models should start within the current market design and regulatory context, investigating how to *facilitate* cost-effective and market-based storage deployment and operation in the EU, without taking any *a priori* position about ad-hoc, particular arrangements to encourage investments in storage.

The future role of the various electricity storage technologies will depend not only on their respective technical and cost developments, but also on how alternative sources of the same services as well as the whole power system evolve. It will make a difference whether we move towards 'European-wide energy superhighways' with massive solar energy being transported from North Africa to Central Europe, huge amounts of offshore wind energy being produced in the North Sea and nuclear energy from Eastern Europe contributing to Western European electricity supply; or whether we move instead towards a system in which further increased penetration of small-scale distributed generation and successful demand side management lead to rising local energy autonomy.

Whereas the first scenario probably would involve an increasing role of large-scale bulk storage facilities, in the second scenario smaller-scale storage systems and thermal storage directly connected to end-users would be key and the amount of electricity to be transported across the power system would be reduced. Also the penetration of for instance electric vehicles and heat pumps combined with heat storage and their potential for controlled charging/discharging in the coming decades is highly uncertain. Given all the above-mentioned uncertainties, any ad-hoc incentives for storage investments within the current regulatory system should be carefully designed, in order to avoid future stranded costs.

The aim of this report is to formulate policy recommendations for the EC (DG ENERGY) on how to allow for the cost-effective and market-based development, deployment and operation of electricity storage in the EU. This report does not give an answer to the question of how many or what kind of electricity storage will be needed in the future system – this would imply defining the future power system first, which is clearly out of the scope of this report. Instead, the report discusses whether the benefits that electricity storage could provide to power systems are properly recognized and rewarded by existing market design and regulation in Europe. Thus, the logic line of reasoning consists of the following questions: What are the drivers for electricity storage deployment in power systems and is electricity storage a special class of assets for the future power system (Chapter 2)? Which conditions may have led to a more ambitious development and use of electricity storage in some non-European countries, as compared to the EU (Chapter 3)? What are likely viable business models for electricity storage (Chapter 4)? Do current market design and regulation allow for these business models, and if not, are significant changes recommended or not (Chapter 5)? Chapter 6 concludes.

1. Electricity storage: A special class of assets for the future power system?

The basic question to be addressed here is whether electricity storage does represent a special class of assets which calls for innovative concepts in terms of business model, market design and regulation. A preliminary question to be answered is whether alternative means of flexibility are fundamentally different from storage regarding the services they can deliver. Another issue is whether electricity storage as a particular system component will play a special role in the future European power system, given the expected changes in generation patterns and control mechanisms.

1.1 Are alternative means of flexibility fundamentally different?

In the broad sense, the basic energy-storage activity can be considered as "to take energy whenever and in whatever form it is available, convert it to whatever form is best for storage, and then reconvert it to whichever form is best for use at the time we need it" (Fink and Beaty, 1978). This does not only include pumped hydro or battery systems, but for instance also thermal storage or capacitors. *Electric* energy storage, according to this definition, only represents a sub-set of energy storage technologies, in which the energy taken in and retrieved from has the form of electricity. It can be characterized as a "tri-able"; it is (1) able to *consume* electricity, (2) able to *accumulate* this energy; and (3) able to (re-) *produce* electricity.[1]

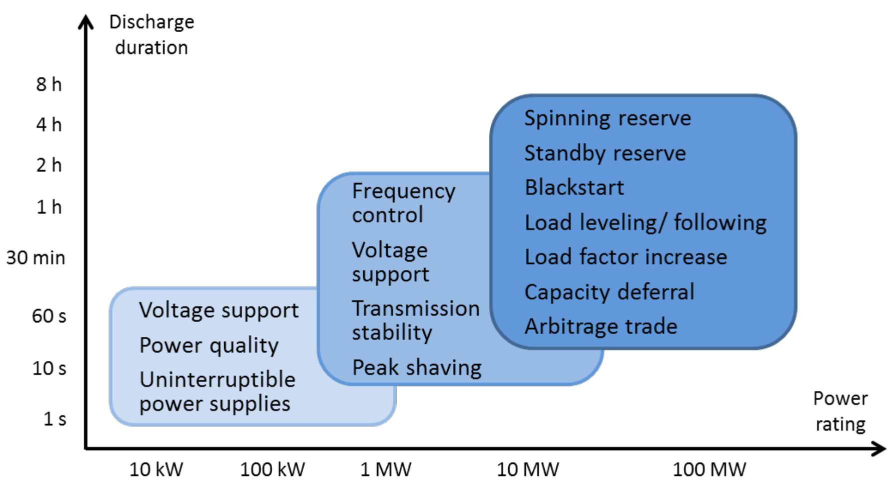
1 For many storage devices this implies that electricity is converted into another form of energy, in which it is stored, and finally reconverted into electricity. However, this is not true for all technologies. For instance, capacitors store energy within an electric field.

Electricity storage is gaining attention nowadays as its quick energy conversion capacity is considered as enabling the power system to function in a more flexible way, which could be especially helpful given the magnitude of intermittency associated with renewable energy sources. The value of electricity storage is related to each of the "tri-ables" introduced above. Functions (1) and (3), i.e. the abilities to provide downward and upward adjustments to the system, can contribute to the production/consumption balance in different timeframes, the former in absorbing excessive or low-cost electricity, the latter in covering a production deficiency or replacing high-cost electricity generation. The value electricity storage can provide is related to the technical characteristic of the storage facilities, such as response time (How fast it can react [ms-s-min]?) or power rating (How much imbalances it can correct [kW-MW]?).

Function (2) is related to the accumulation of energy over time, giving rise to the possibility of inter-temporal arbitrage. This inter-temporal arbitrage action has its own value, originating from better allocating production resources over time and is related amongst others to the energy rating (How long it can last [s-min-hours]?). These three functions can be valued by providing different services to individual actors in the electricity system or to the whole system. Existing literature also presents extensive discussions categorizing services that electricity storage can provide by stakeholder group (e.g. EAC, 2008; EPRI, 2010; Sioshansi, 2010; He, 2011). Figure 1 maps selected applications that represent different combinations of power rating and discharge duration.

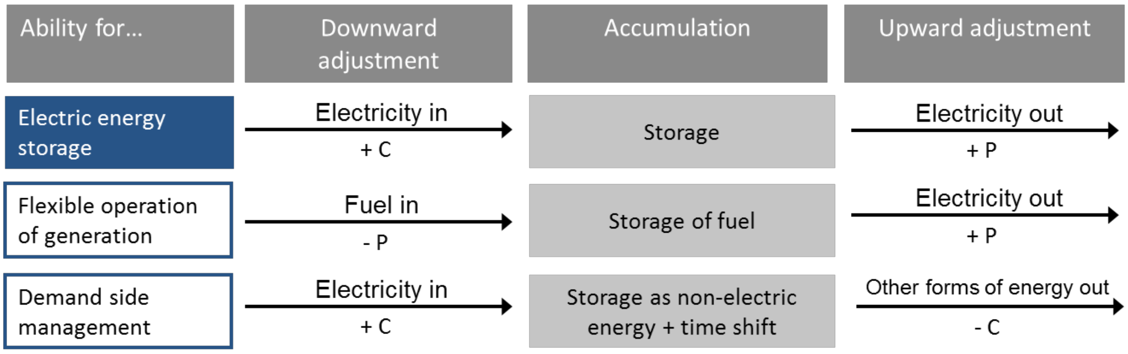
The actual value that storage can realize will also depend on various other technical characteristics of the technology employed, such as roundtrip efficiency, possible cycles and lifetime, or self-discharge. These vary substantially among alternative technologies (see Table 6 in Annex 1). Further factors determining the economics of electricity storage originate from

Figure 1: Selected applications of storage according to power and energy functionalities



Source: Own depiction following ESA (2000)

Figure 2: Alternative means of flexibility



[+C/-C means an increase/decrease in consumption; +P/-P means an increase/decrease in production]
Source: Own depiction

economic conditions (such as electricity price volatility or the cost of alternative means of flexibility for being used in the respective applications) as well as from the regulatory framework defining rules for e.g. market access, grid tarification or renewable support schemes. "Electricity storage" is not one single given technology with a single outcome but a set of differentiated technologies with different outcomes, which could make some of them more or less suitable to certain circumstances than others.

One should be aware that there are several alternative means of flexibility in generation, demand and even in networks. This includes a more flexible operation of existing generation units (including conventional generators but also the possibility of curtailing RES-based installations); investments into new, more flexible conventional power plants; demand side management including a variety of measures such as smart contracts triggering demand response, smart appliances that can be controlled through suppliers, aggregators or grid operators; thermal storage devices and electric vehicles (with or without vehicle-to-grid capabilities). The grid is no flexibility means in itself but rather a vehicle of flexibility sources. It allows sharing flexibility over a larger geographic area.[2]

As summarized in Figure 2, alternative means of flexibility can also be characterized by the three functions introduced above; all are able to react to the system requirements of downward or upward adjustment and also include the opportunity to benefit from inter-temporal arbitrage. Regarding a more flexible operation of conventional generators, downward adjustment is equivalent to a decrease in production and upward adjustment is provided in a similar way as for electricity storage, namely via a temporary production increase. Accumulation here is related to storing the fuel. Regarding demand side management, downward adjustment implies an increase of consumption, for instance resulting from a demand shift or from charging thermal storage devices. Upward adjustment respectively does imply to temporarily consume less.

Dissimilarities come from the form of energy in the conversion and accumulation processes. The main technical differences relevant for the services that alternative means of flexibility can provide originate from **quantity and degree**, i.e. response time [ms-s-min]; power rating [kW-W-MW]; and energy rating [kWh-MWh]. For instance, selected electricity stor-

2 This could change with new devices (facts, DC stations, etc.) since managing flows might become more flexible in the future.

age technologies such as flow batteries could outperform generation flexibility in terms of response time. In terms of energy rating, they are rather constrained due to the limited reservoir capacity, whilst the fuel storage for flexible generation is much less problematic and could be considered as unlimited in the operational strategy.

Furthermore, different flexibility means are subject to geographic constraints and natural endowment. Pumped hydro facilities can only be constructed at locations where water and a sufficient difference in height are available or can be created; CAES units require an underground salt dome cavity. The use of other technologies might rely on high operating temperatures and thus sophisticated thermal insulation systems (NaS or ZEBRA batteries) or on the use of dangerous chemical substances (Pb-acid batteries). There also might be concerns regarding negative effects on human health associated with strong magnetic fields for SMES. The potential for demand response is limited, too; and one has to be aware that a more flexible operation of conventional generating units implies lower load factors and thus impacts their economics. The expansion of grids alone also cannot mitigate all types of supply fluctuations, for instance solar PV units won't generate any electricity in the whole European system during night hours.

Consequently, one source of flexibility is not necessarily always superior to another – its value depends on the required technical performance and cost. **The often expressed need for electricity storage to enable decarbonization is an economic question**; it will depend on costs and benefits of the respective technology as compared to other options. The key issue faced by power systems today – and even more in the future – is the need for (different forms of) system flexibility and the value of flexibility means comes from the match between the required functions and their techno-economic characteristic. Electricity storage, in its various forms, is only one type of solution and alternative means of flexibility can be both substitutes for providing specific services to the grid and complements given the quality and quantity of flexibility required.[3]

1.2 Does electricity storage have a special role for the future European power system?

A second question that has to be investigated is whether electricity storage actually has a special role in the future European power system. After summarizing drivers for the development and deployment of electricity storage in the past, new drivers in the future system which could give birth to a special role of storage are discussed.

1.2.1 Drivers for development and deployment in the past

The 'old world' European power system was developed based on the traditional paradigm of generation and grid following demand. It resembled more a top-down control and planning system with the major challenges associated to real-time adjustments in production to

3 One could think about extreme situations where electricity storage might be the only alternative technology. Very favorable conditions for RES over a large geographic area could lead to a situation of over-supply that mirrors in zero (or even negative electricity prices), with conventional generators not being able to further reduce their output and load being completely saturated. On the other extreme, the system could be extremely short in supply without any further conventional backup capacity being available anymore and all demand response potential being already activated. In these cases, storage might not be exchangeable. However, these situations are very rare, and with increasing system interconnection will become even less likely.

respond to demand variations. Pumped hydro storage (PHS) has been already used for nearly a century to provide, besides oil-fired turbines and diesel motors, flexibility to the system. It has been further developed in the 1980s to balance less flexible conventional and nuclear generators. Vertically integrated utilities invested in storage to replace peaking generation capacity. UCPTE and NORDEL were mainly created (1951 and 1963, respectively) to exploit the complementarity between hydro and thermal systems.[4]

Following the two oil crises in the 1970s, oil and natural gas markets saw dramatic price increases. Together with concerns about security of energy supply, this situation triggered substantial investments in new coal-fired and nuclear power plants. The increasing share of inflexible base-load generation combined with high fuel prices made electricity storage an interesting option to provide ancillary services. During the 1970s, investment costs for PHS and CCGT plants were comparable (Denholm et al., 2010), and thus, given the lower variable costs of PHS, the business case of electricity storage was clearly more attractive than that of conventional alternative sources of flexibility. Substantial new PHS capacities have been added (Figure 12 and Figure 13 in Annex 1), and various R&D programs targeting not only energy efficiency and alternatives to oil, but also energy storage technologies were initiated.

The framework conditions changed again during the early 1990s, when falling fuel prices and technical improvements made CCGT a more economic option to provide flexibility to the system. Thanks to increases in efficiency and cost reductions, investment cost for CCGT capacities fell to about half of the investment cost of PHS in the early 2000s (Denholm et al., 2010). Besides, investors also take into account other factors that increase project risk – it takes more than five years to construct a PHS facility (compared to 2-3 years for CCGT; see BC Hydro, 2010; Blesl et al., 2008) and administrative hurdles might complicate the process further (complex permitting procedures, public and environmental opposition, etc.). As a result, interest in developing and deploying storage technologies declined and only limited capacities have been added during the last 25 years.

1.2.2 Drivers for development and deployment in the future European power system

Electricity storage only recently started to receive ever growing attention from utilities, TSOs, manufacturers, researchers and policy makers. Within FP7, a large call for proposals has been opened, the European Association for Storage of Energy (EASE) has been established in 2011, conferences and workshops all over Europe are organized at least monthly, and various academic papers and reports discuss the future role of electricity storage as one key technology enabling decarbonization (see e.g. EAC, 2008; Kaplan, 2009; EPRI, 2010, Eyer and Corey, 2010; He et al., 2011).

The EU has committed to reduce GHG emissions to 80-95% below the 1990 levels by 2050 (EC, 2011). Meeting the 2020 objectives alone will only help to achieve about half of the 2050 decarbonization goal; thus, stronger measures are required and indeed, all scenarios in the 2050 Energy Roadmap show that electricity will have to play a much greater role, contributing substantially to the decarbonization of the

4 Remark: Large hydro reservoirs and run-of-river power plants are no electricity storage assets in the narrow sense; they are not able to 'consume' electricity to charge a reservoir. However, these units can provide certain flexibility on the generation side delivering upward adjustment services. A decision has to be made on whether to use them now or later, which is also discussed in a huge body of academic literature (see e.g. Jacobs et al., 1995; Pérez-Díaz et al., 2010; or Catalao et al., 2012 and references therein).

transportation sector and almost doubling its share in final energy demand to 36-39% in 2050. Final electricity demand increases in all scenarios. Therefore, the power system is expected to undergo structural changes at all levels and with 57-65% a significant level of decarbonization of electricity generation should already be reached in 2030. The share of renewable energy achieves 55% to even 97% (high-RES scenario). This is also in line with the objective of the European Industrial Grid Initiative as part of the SET-Plan to enable the integration of up to 35% of electricity from dispersed and concentrated renewable sources by 2020 and a completely decarbonized electricity generation by 2050 (EC, 2009b).

The current renewed interest in electricity storage development and deployment is motivated by new features of the European power system one the one hand, and changes in the economics of electricity storage on the other:

(1) New features of the European power system: The supply side faces an increase in variability and intermittency of production. Wind and solar energy sources are generally not dispatchable (apart from solar thermal units) and unpredictable wind gusts and cloud movements mirror in sudden decreases and (re-)increases of electricity generation. Large-scale remote RES, concentrated in specific areas and typically located far away from consumption centers, will be responsible for a substantial share of electricity generation in the 2020 and 2050 context, and also small-scale distributed generation will continue to gain in importance. There is a trend towards smart grids, and on the demand side, we expect an increasing use of smart appliances and active demand response. Electric vehicles might see a substantial market penetration (Table 8 in Annex 1). Thus, there are various drivers of system change, at transmission (connection and integration of large-scale RES, increasing system interconnection …) and distribution level (connection and integration of small-scale RES, transition towards smart grids, increasing penetration of electric vehicles ...). One can anticipate a *growing interplay between transmission and distribution levels* – the connection of large amounts of distributed generation and increased demand response, etc. – that would change flow patterns in both transmission and distribution grids. Storage could enable a better management of such new flow patterns.

(2) Changes in the economics of electricity storage: Technical advancements and innovation and a reduction in the costs of different storage technologies have improved and probably will continue to improve the economics of electricity storage for certain applications compared to alternative means of flexibility. Nevertheless, changes in market design and regulation are needed to remove barriers for the development and deployment of electricity storage (see Chapters 4 and 5 for an in-depth investigation).

It is stressed that this report will focus mainly on electricity storage, while being conscious that the value of storage needs to be assessed under a **double uncertainty**: On the one hand, there is uncertainty concerning the direction and timing of innovations in storage technologies, i.e. regarding their technical and cost evolution; on the other, there is uncertainty concerning the pace of change in generation, demand and grid flexibility. Also future innovations in information and communication technologies probably will have an important impact on system functioning (e.g. "smartness of grids and appliances") and the use of different technologies in certain functions (e.g. vehicle-to-the-grid). Therefore, this report is aimed at providing an analytical framework for the economics and regulation of electricity storage, which should be also applicable to other flexible means. Market design and regulation should permit the development and deployment of storage technologies and provide a level-playing field instead of building artificial barriers.

1.2.3 Roles of storage in the future power system

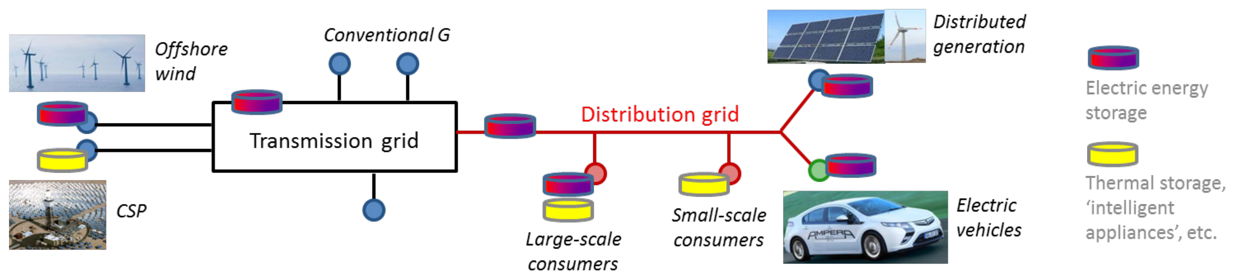
Table 1 summarizes major areas where electricity storage could play a role in moving to a low-carbon, but at the same time highly reliable, power system in a cost efficient way. This includes amongst others to enable a high share of RES in the generation mix via capacity accommodation and capacity firming, to provide ancillary services to support grid stability and quality of supply, or to complement demand side management and active demand response. Storage might also be an interesting mean to address congestion and optimize grid investments. Two issues have to be considered here, the cost of grid expansion but also possible problems associated to the timely availability of the new infrastructure. The construction of new electricity lines might involve a substantially higher administrative burden, public and environmental opposition, and longer permitting procedures compared to electricity storage units. In fact, the past has shown that wind cur-

Table 1: Possible roles for electricity storage in the future power system

'Old world'	Future system challenges	Implications	Possible roles for ES
Limited RES	Massive RES integration *(Distributed generation as well as large-scale remote RES)*	- Need to connect RES at both transmission and distribution level - Need to smooth variability and intermittency - Need to ensure system security in the longer-/mid-term and in real-time	- Optimization of trans-mission and distribution grid investment - RES capacity accommodation and capacity firming - Backup capacity for system operation / provision of ancillary services - …
Top-down control system	Trend towards smart grids, smart appliances, and demand response	- Need to manage two-way power flows - Need for more sophisticated system control	- Buffering capacity to facilitate smart operation of the grid - Demand-side optimization of consumption pattern - …

Source:: Own depiction

Figure 3: Possible locations of application in the future power system



Source: Own depiction

tailment might be inevitable in present systems,[5] and the situation we saw in Germany (with a grid operator claiming to miss financial resources to connect further offshore wind farms to the core grid) could be turned into an 'opportunity scenario' for electricity storage.

In the past, electricity storage was mainly employed in the form of large-scale, bulk, centralized units providing storage over relatively long durations (mainly PHS) as well as some systems providing fast response (batteries, flywheels). Today, there is an emerging interest in small-scale, decentralized storage and indeed, in the future power system electricity storage could fulfill a variety of functions and provide benefits to various stakeholders. It might be connected directly to the transmission or distribution grids, to renewable generators, or to consumers. Also electric vehicles technically can provide the different storage functionalities as discussed above. Besides electric energy storage in the narrow sense, also thermal storage devices might see interesting applications at consumer level or in combination with large, remote concentrated solar power facilities. Thus, electricity storage can be located closer to generation or closer to load; it could be operated in a more centralized or in a more decentralized manner; it can be a 'shared resource' benefiting the whole system or rather a more 'dedicated resource' benefiting a single actor. [6]

Hence, there are alternative possible scenarios regarding the location, operation manner, and the main services electricity storage could provide. The future role of storage will be determined by the (i) degree, (ii) location and (iii) timing of the flexibility needs introduced by the evolution of the European power system, as previously presented. These three features of future flexibility needs are not yet clear to date. They could be highly related to how Member States proceed their renewable targets, by developing large-scale, remote RES (like offshore wind or solar in northern Africa) or smaller-scale distributed generation, or both. It is out of the scope of this report to forecast the evolution of the future power system. Rather, this report focuses on how to identify and suppress market and regulatory barriers to allow storage playing its most adequate roles in different scenarios.

5 This has happened for instance in Denmark, a country with a large wind capacity but at the same time also strong reliance on combined heat and power plants for district heating, which need to be kept running for heating purposes in cold seasons.

6 It should be noted that storage will only fulfill a 'local function' if there are network constraints. This also is true for storage connected directly to a renewable generator. In the absence of network constraints it would have to be investigated whether a larger-scale centralized storage might not be more economic than a larger number of individual small-scale storage units.

2. Technology review: Alternative technologies and their deployment

The following chapter provides an overview on existing storage technologies and their current level of technological maturity and deployment. Some interesting international experiences are highlighted in order to discuss which conditions might have led to a more ambitious development and use of storage in selected non-European countries. Finally, guidelines for public support policies targeting RD&D are provided and the need for joint action at supra-national level is discussed.

2.1 Overview

Electricity storage technologies can be classified based on the underlying physical principles of the energy transformation process. Accordingly, three major categories are distinguished: (1) mechanical storage (including pumped hydro storage (PHS), compressed air energy storage (CAES), and flywheels); (2) electrochemical storage (including conventional batteries, advanced high-temperature batteries and flow batteries); and (3) electromagnetic storage (including superconducting magnetic energy storage (SMES), superconductors and supercapacitors). These technologies differ widely in terms of technical and economic characteristics. In the following, we highlight selected key parameters; for a more detailed technical description see Annex 1 of this report as well as various available technical reports (e.g. EC, 2001; Baker, 2008; Naish et al., 2008; EPRI, 2010; JRC, 2011).[7]

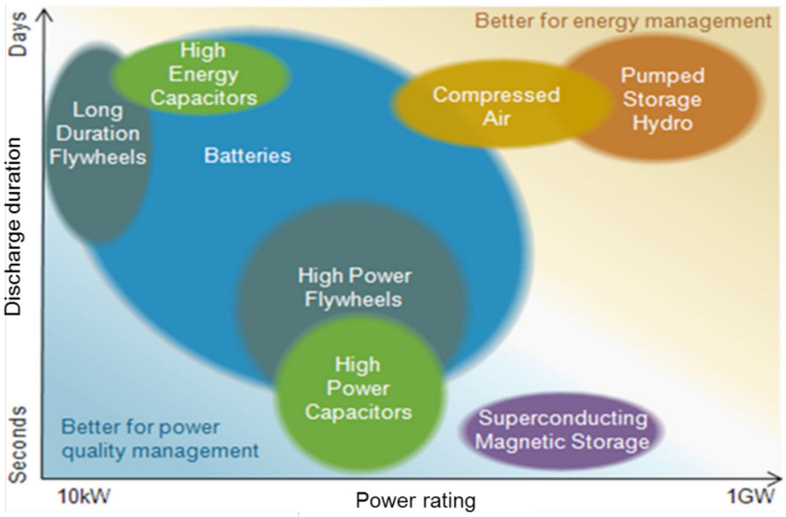
The response time of electricity storage technologies differs widely. It ranges between five to 15 minutes for CAES facilities over seconds to minutes for pumped hydro and a few seconds for flywheels, down to milliseconds for Li-ion and innovative lead batteries. Together with energy- and power rating this determines the suitability of storage technologies to provide specific services to the power system (Figure 4). PHS and CAES facilities have a large capacity and long discharge duration, which are important attributes for energy management applications. In contrast, most battery technologies, flywheels, supercapacitors or SMES are technologies that allow for smaller-scale energy storage. They are especially suited to providecapacity and power quality management.

There is also wide diversity regarding various other technical parameters. *Energy density* with 150-250 Wh/kg is especially high for advanced battery systems. Flywheels with 400-1600 W/kg have by far the highest *power density*. Whereas *self-discharge* for PHS or existing types of CAES is negligible, it is a substantial parameter for certain battery systems (e.g. ~12%/d for NaS batteries) or flywheels (20-100%/d). NaS and ZEBRA batteries, in contrast to conventional batteries, need *operating temperatures* in the range of 300-350°C. *Roundtrip efficiency*, *technical lifetime* and the *effect of frequent charging and discharging* are further parameters having an important impact on the economics of individual technologies targeting specific applications. For more details see Table 6 in Annex 1.

While many forms of electricity storage have been installed and different battery types are currently showing high market growth rates (Peters et al., 2008), PHS is by far the most widely used technology today with more than 127 GW of operating capacity worldwide. This observation is not surprising, since PHS is

7 Remark: In the 2050 context, all forms of energy storage have to be considered. This includes also thermal storage. In fact, thermal storage in some applications can be functionally equivalent to electricity storage in the narrow sense, e.g. when storing thermal energy from solar radiation that later is converted into electricity (e.g. at CSP plants), or when converting electricity into a form of thermal energy that later substitutes for electricity use in e.g. electric heating/cooling appliances. Thermal storage covers a power range of a few kW (buildings) up to more than 100 MW (CSP) with discharge durations of minutes up to several hours.

Figure 4: Categorization of selected storage technologies according to discharge duration and power rating

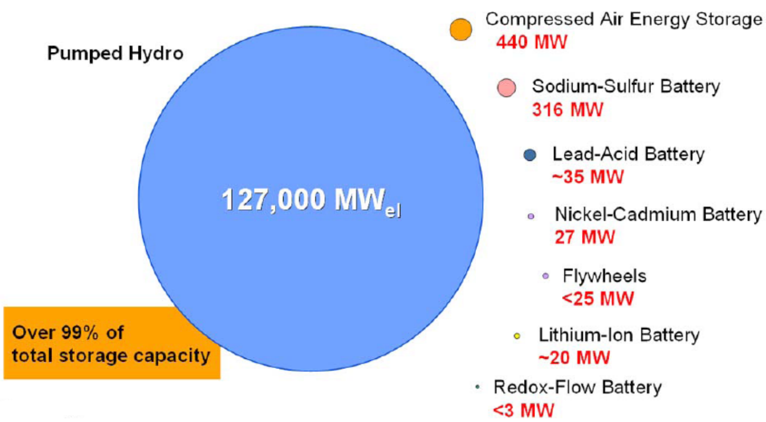


Source: EIA (2012)

a mature technology, and currently the only one that has been proven commercially to be viable.

The market for energy storage is quite vibrant, with start-ups co-existing alongside well-established firms. This reflects the importance of innovation. For PHS, for instance, while Alstom is one of the leading manufacturers worldwide commercializing this technology, smaller firms such as Gravity Power Inc. (US) or Riverbank Power (Canada) offer new alternative solutions based on traditional PHS technologies. The former exploits gravity power, while the latter offers underground storage solutions. While the first CAES was developed in Europe, the US has witness a surge in firms offering this storage solution nowadays. American and European manufacturers are also very active in flywheel storage technologies. Asian companies seem to focus their commercial strategy on battery solutions. The leading developer for supercapacitors at the moment is the US-based Maxwell Technologies. Further information on storage manufacturers can be found in Box 1.

Figure 5: Installed capacities worldwide



Source: EPRI (2010)

Box 1: Storage manufacturers

For PHS, Alstom (FR) is a major market player when it comes to a "standard" PHS facility, capturing about half of the market. Other European firms proposing PHS solutions include Voith Hydro (DE) and Indar Electric of Ingeteam (ES). PHS projects in Europe typically are undertaken by consortia of firms providing construction expertise, turbines, generators and other components. For instance, ABB, Alstom Hydo Austria and Andritz VA Tech Hydro were involved in the installation of a PHS unit in Carinthia, Austria. Also Japanese manufacturers such as Toshiba and Hitachi are active in this market. Some American firms are proposing new, innovative designs. In particular, Gravity Power currently is commercializing a system ('Baptized Gravity Power Module') which eliminates the siting and geological requirements of PHS. The technology uses a very large piston that is suspended in a deep, water-filled shaft, avoiding site constraints. Likewise, the Canadian-based Riverbank Power is proposing to commercialize an underground PHS system.

Alstom has also participated in the construction of the world's first **CAES** facility in Huntorf (DE) as well as in an Advanced Adiabatic CAES facility funded under FP5. Nevertheless, US firms are now establishing in the development and construction of this technology. These include for instance the CAES Development Company, which was initially involved in the Norton Energy Storage facility in Ohio, Ridge Energy Storage and Grid Services LP, Dresser-Rand, General Compression, which has recently been granted a ARPA-E grant for developing CAES facility with faster ramp-up time, Energy Storage and Power LLC, which commercializes 2nd generation CAES and which was involved in the Alabama CAES facility, or Sustainx. Moteur Development International (FR) is developing motors based on compressed air for vehicle applications.

Several US firms are marketing **flywheel** storage technologies. Beacon Power (US) appears to be the current market leader for flywheel solutions for grid applications. Other manufacturers include the Texan Active Power, Washington-based AFS Trinity, Pennsylvanian Tribology Systems, Californian Pentadyne Power, and Californian Vycon. The latter did also participate in a storage project in the UK (Sun Gard Availability Services). The Canadian-based Temporal Power, has developed and commercialized a flywheel technology that can hold much more energy than existing ones. Other North-American firms, like the Canadian Flywheel Energy System Inc. and Washington-based AFS Trinity, specialize on flywheel storage technologies for transportation. The Australian PowerStore has developed a very rapid energy source and sink system based on flywheels. This technology is installed in Graciosa and Florès islands (Azorean Archipelago, PT) to integrate RES. In Europe, the Swiss ABB commercializes the technology as well. ENERCON (DE) commercializes a 200 kW flywheel storage that can be used in conjunction with a stand-alone wind power system. Pillar Power Systems (DE) proposes flywheel systems of smaller sizes (6, 15.5 and 21 MW). Other manufacturers include Urenco Power Ltd (UK) and Riello UPS RPS (IT).

Maxwell Technologies (US) is clearly the leading industrial player for **supercapacitors**. Other major developers include Panasonic, NessCap, Elna, or NEC Tokin. These are typically located in Asia. In Europe, supercapacitors are manufactured by IDS (Switzerland). The Russian ESMA is collaborating with Saft, a leading French battery company, to develop nickel-based capacitors.

NGK Insulators (Japan) is the market leader for **NaS battery** systems. The company has developed this technology in collaboration with Tokyo Electric Power and is now a strong player in marketing the technology. In Europe, MEA-DEA (Switzerland), acquired by FZ Sonick (IT), as well as FIAMM (IT) develop and commercialize an alternative storage technology based on sodium, known as Sodium-Nickel-Chloride (or ZEBRA) batteries. Also General Electric entered the market for this last class of batteries.

Exide Technologies (US), EnerSys (US) and C&D Technologies commercialize storage solutions for grid or utility applications based on **lead-acid battery** solutions. An advanced lead-based storage solution, PbC batteries, is commercialized by Axion (US). Main manufacturers of Li-based battery solutions include A123 Systems and Altair Nanotechnologies (both US) and Saft (FR). Besides, the Chinese company Winston currently is proposing an alternative **Li-based battery** storage solution, which the company claims to be environmentally friendly. The technology is mainly intended to be applied for electric vehicles. In Europe, Siemens (DE) is also stepping into this industry by proposing a modular Li-based power system.

Finally, European firms are relatively absent regarding the manufacturing of **flow batteries**. Major industrial players in this segment are American or Asian. These include Prudent Technologies (China and US), designing and manufacturing Vanadium-redox batteries; ZBB Energy (US), being the only firm marketing Zi-Br flow batteries; and EnStorage (Israel), marketing lower-cost flow batteries based on a H2-Bromine technology.

2.2 Alternative technologies and their deployment in Europe

In Europe, there are about 45 GW of pumped hydro storage operating today. In addition, there is one CAES facility installed in Germany (see Chapter 4.2 for further details thereon). Other storage technologies only represent very minor capacities so far (see Table 2).

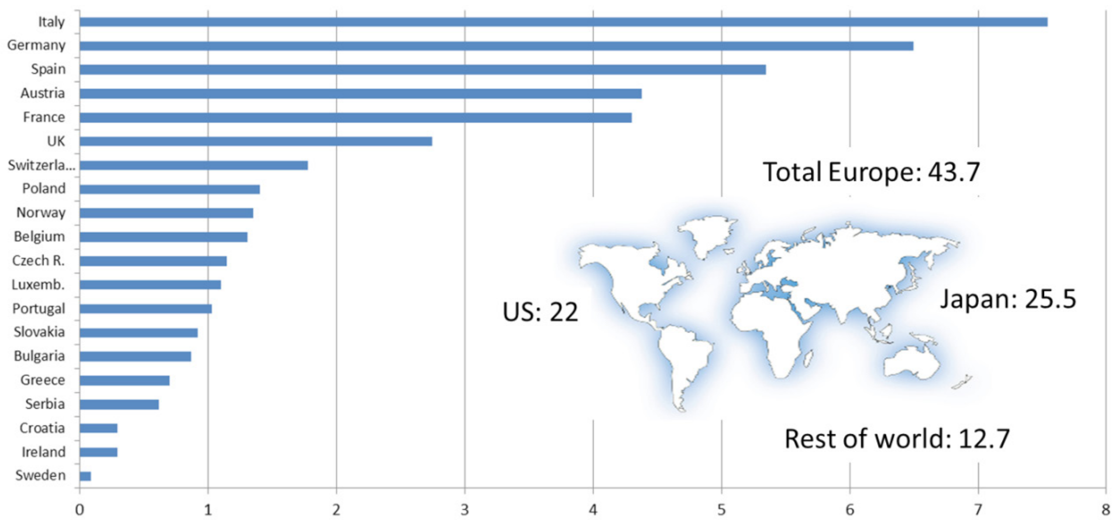
Table 2: Installed electricity storage technologies in Europe

Technology	Installed capacity (MW)
PHS	45,600
CAES	290
NaS battery	few MW
Pb-acid battery	20-30
Lithium-ion battery	~20
Redox Flow battery	~1
Others	n.a.

Source: Prestat (2011)

PHS deployment is not uniform among countries. As shown in Figure 6, the majority of facilities is concentrated in the Alpine regions of France, Switzerland and Austria, as well as in Italy, Germany and Spain. Despite the long history of PHS in Europe, until the last two decades the pump-turbine systems were operated at constant speed by synchronous machines (Suul, 2009). This brings rigidity of output level control as well as ancillary services provision, and there is still room for technical improvement which can bring numerous economic benefits in light of the variability challenges posed by a massive integration of renewables (Alstom, 2011). Recent upgrades of PHS capacities mainly came from a retro-fitting of existing installations, from adding pumped storage to conventional reservoir-based facilities, or from an increase in power rating. New innovative concepts under consideration include energy islands offshore or the development of underground PHS facilities in former mining areas (see Annex 1 for more details).

Figure 6: Installed PHS capacities in Europe and worldwide in 2008 [GW]



Source: Own depiction using data from www.eia.doe.gov

Although components of the CAES technology can be considered as mature, deployment of this technology both in Europe and elsewhere remains limited, mainly due to the challenges related to geological requirements.[8] Indeed, Europe counts only one unit operating in Huntorf, Germany (turbine capacity 320 MW, compressor capacity 60 MW, start-up 1978). An *adiabatic CAES* facility is considered for development in Germany, too. In the ADELE project, RWE Power, General Electric, Züblin and DLR are working together to develop a first demonstration plant in Stassfurt (360 MWh, 90 MW), which is located in a region with a lot of wind generation. In this adiabatic process, the heat of the compressed air remains in the process for use in power generation. Hence, compared to existing CAES facilities, higher efficiencies (~70%) can be reached and CO_2 emissions are reduced since during the heating process no gas will be used anymore. The project is supported by the German Ministry of Economics and Technology with funds from the COORETEC program.

Where flywheel technologies are concerned, several demonstration projects have been launched. In particular, the Spanish project SA2VE tests applications of the flywheel technology in railway transport, energy management for buildings, and power supply quality. A flywheel facility also has been installed in 2005 in the Flores Island of the Azores Archipelago as a means to allow for a higher integration of wind power in this island system. Powercorp, an Australian-based company, designed this facility with the aim of providing peak lopping and spinning reserves. The positive results obtained in terms of network stability have encouraged the implementation of a similar system on the neighboring Graciosa Island (Faias et al., 2008). This installation is particularly interesting in the sense that the facility has also implemented a system that addresses the inherent problem of wind turbines operating as negative load to offset diesel fuel.[9]

Energy storage in grid-connected public transport systems, such as railway, underground and tram, also has been an issue for some time (see also EC, 2001). Flywheels and supercapacitors probably will be the technologies of choice for this application as they have a high power output and their energy content is adequate. An energy storage solution based on a flywheel has already been installed in the Hannover (Germany) city-tram system: 29 % of the consumed traction energy is energy recovered while braking. Each flywheel is capable of storing up to 7.3 kWh of energy, which is equivalent to about 26 liters of petrol (Eurelectric, 2004b).

The deployment of electrochemical storage technologies in Europe to support grid activities seems to be rather limited. Even if some of these technologies are currently available, it seems that their usefulness for bulk storage and to support RES integration still remain to be demonstrated. Hence, the deployment of these technologies is often related to demonstration and/or test projects. Among various electrochemical storage technologies, Pb-acid batteries are commonly used in stationary and automotive applications. For instance, the project DEMO-RESTORE, financed un-

8 In the US, for instance, the existing CAES facility in Alabama was developed in a salt dome, a geological phenomenon uncommon outside the Gulf of Mexico region (Succar and Williams, 2008). A proposed facility in Iowa was canceled in July 2011 due to insufficient geologic conditions after a five year testing period (Sioshansi et al., 2012).

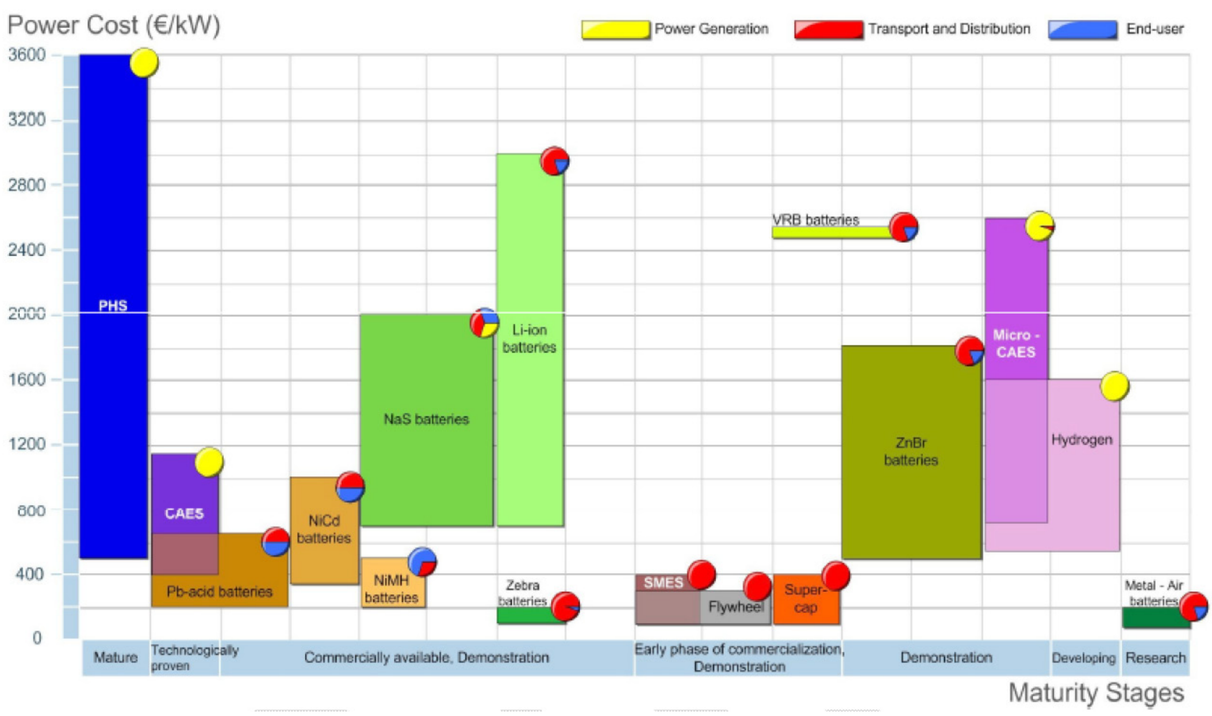
9 There are several flywheel facilities under development in the US, too. In particular, Beacon Power, a provider of fast-response flywheel energy storage for frequency regulation, is currently developing three new facilities: one in Stephensontown (NY) through a DOE load guarantee (43 mn USD), one in Hazle (PA) through a DOE stimulus grant (24 mn USD) and one in Glenville (NY). The company has also received a 2.25 mn USD grant from the DOE under the ARPA-E program to develop a flywheel for new applications.

der FP6, intends to test the robustness of Pb-acid batteries as a support to PV systems. Ni-Cd batteries are less developed despite their advantages over Pb-acid batteries, principally due to the toxicity of some of the materials used and challenges related to the conformity with EU regulations on batteries and waste (Directive 2006/66/EC). Concerning advanced battery technologies, Germany has developed the world's largest Lithium-ceramic battery, with a power rating of 1 MW and a storage capacity of 700 kWh. Lithium-titanate batteries are another emerging Li-based technology. Compared to other commercially available lithium batteries, it features high efficiency, high cycle life (~10,000 full cycles), high power density, at the trade-off of higher capital cost (~2000 EUR/kWh) and lower energy density. There are several demonstration projects on NaS batteries (Berlin-Adlershof, Gran Canaria, and Reunion Island). A test facility in Livorno, Italy, is undertaking tests to consider grid applications of ZEBRA batteries. Demonstration projects of flow batteries include a facility in La Gomera, the Sorne Hill wind farm in Ireland and the Riso Research Institute in Denmark.

Spain is also involved in demonstration projects for supercapacitors. In particular, the STORE project in Canary Island is a demonstration project for ultracapacitors. The FP6 project HyHeels considers supercapacitors as a means to optimize hydrogen-based systems. As for SMES technologies, there are several successful demonstration projects, in particular in Germany, Finland and France. These projects operate at 20kW. Research prototypes of the SMES have also been developed in Italy, Germany, Finland and Spain.

Being an immature technology, hydrogen-based sto-

Figure 7: Technical maturity of different technologies



Source: JRC (2011)

age systems are, unsurprisingly, not highly deployed in Europe and elsewhere. The first demonstration project is run in Norway, Utsira Island, since 2004 as a backup for wind farms in remote areas. Other demonstration projects in Europe are in Unst (Shetland Islands, UK), Naskov (Denmark), Keratea (Greece) and in Galicia and Aragon in Spain (see also Institute for Energy and Transport, 2011). A large hydrogen-based power plant with a rated capacity of 1 MW, operated by a joint venture of the chemical companies Solvay and BASF, recently has started operation at the port of Antwerp (Belgium).

As already indicated above and illustrated in Figure 7, most storage technologies are highly immature. There are some promising technologies, but it is still too early to predict their potential and there is huge uncertainty regarding the technological evolution and also regarding the future cost of different technological options that might be applied to provide certain services. Figure 7, however, has to be used carefully. First, uncertainty regarding cost data increases substantially the more immature the respective technologies are. Often, no large-scale experience exists (especially for micro-CAES and

Box 2: Current RD&D priorities and recent initiatives

The EU is (co-) funding research on technologies for energy storage for stationary and transport applications since the mid-1980s through its Framework Programmes (starting with FP2). In the past, this included mainly R&D on materials, processes and components for energy storage, as well as energy storage systems integration. A good overview on *current* European RD&D priorities and recent initiatives is provided by JRC (2011). Europe today still has a strong position in large-scale energy storage technologies, namely PHS and CAES (including ongoing research activities targeting innovative concepts such as adiabatic CAES). However, international competitors enter the market at quick pace and for smaller-scale storage technologies the position of European manufacturers is relatively weak. The battery market is dominated by Asian companies.

Current RD&D activities target the whole portfolio of storage technologies and initiatives are undertaken by both the private and public sectors. For instance, the *Association of European Automotive and Industrial Battery Manufacturers* brings together more than 85% of European industrial actors in their field. RD&D efforts target areas such as electrical vehicles and renewable energy storage. The *European Fuel Cells and Hydrogen Joint Technology Initiative* aims to accelerate the development and the deployment of hydrogen-based technologies. Ongoing or *planned projects financed under FP6 and FP7* aim at creating networks of excellence to consolidate the European research in particular fields: "ALISTORE88" (FP6) brings together 23 European research institutes analyzing lithium systems and promoting nanomaterials. "MESSIB89" (FP7) focuses amongst others on flywheels and VRB batteries and "HESCAP90" (FP7) aims to develop a high-energy super-capacitor based system.

In the frame of the *SET-Plan*, energy storage has been identified as one key technology in several areas. This includes the development of storage supporting the integration of RES as well as electricity storage as part of advanced network technologies to improve the flexibility and security of the network. In December 2011 a 'Materials Roadmap enabling low-carbon energy technologies', presenting a proposal for RD&D for the coming decade, has been published. The included roadmap for materials for electricity storage targets cost reductions and technological innovation increasing performance for both energy-application as well as power-application oriented technologies. Precise technical KPIs have been specified. A *Joint Programme on Energy Storage* has been launched at the SET Plan Conference in Warsaw (Nov. 2011). Twenty six partners from 12 Member States work together with the aim to conduct coordinated R&D.

Furthermore, with the creation of the *European Association for Storage of Energy* in 2011, a new platform aiming at building a common industry and stakeholder vision and sharing information in cooperation with similar associations in Asia, Australia and the US, has been initiated. Its work program includes the preparation of storage technology fact sheets and the discussion of possible applications, the development of an economic assessment scheme, the discussion of regulatory issues such as grid access fees, and recommendations for R&D and the energy system evolution.

metal air batteries where R&D is still taking place in the laboratories). Second, these data only reflect expectations about investment costs per kW of installed capacity. But the relevant cost that should be considered are life-cycle cost, which do not only account for the initial investment but also for operation and maintenance as well as residual costs at the end of the life cycle (see also Delille, 2007; Schoenung, 2011).[10] Some storage technologies, especially battery systems, also generate toxic waste during their life cycle. These negative consequences on the environment should be quantified and integrated into cost-benefit analyses, too. Table 7 in Annex 1 provides an overview on Capex and Opex for selected technologies.

In addition, total system costs often will also include associated ICT equipment which is required to enable the use of storage systems in different grid-related applications.

Whereas many stakeholders have presented alternative pathways towards a low-carbon energy system in 2050, there is **no clear vision regarding the future role of electricity storage** in the European power system. To the extent that scenarios consider storage at all, they mainly focus on large-scale, centralized storage. In the EU Energy Roadmap 2050, for instance, balancing and reliability are ensured endogenously in the modeling exercises via import and export flows, investments in flexible thermal units, PHS and some hydrogen-based storage (with excess electricity generation from variable sources being transformed into H_2, which is fed, up to a certain degree, into the natural gas grid). Decentralized, small-scale or thermal storage are not considered.

10 There are also some considerations to enable "2nd life applications" of storage systems. Concretely, batteries used in electric vehicles are exchanged when they lost about 20% of their capacity. These batteries could be used – instead of being recycled – in distributed storage applications (see e.g. Taylor et al., 2012).

On a Member State level, some national (but still only qualitative) visions have been developed recently. Given the national objective of reaching 100% renewables by 2050 in energy and transportation sectors, the Danish government identified energy storage together with intelligent electricity consumption as central components of its future power system (Danish Government, 2011). This includes hydrogen-based storage (injection of H_2 into natural gas grid), strengthening infrastructure to enable access to flexible hydro resources in Sweden and Norway, and using large-scale thermal storage within district heating systems. The UK has a legally binding national target to reduce GHG emissions by 80% by 2050 and the government developed scenarios for the future energy system in its Carbon Plan. The precise role of electricity storage is not clear yet, but it has been recognized that it will depend on the penetration of renewables, the use of electricity for heating purposes, the penetration of electric vehicles as well as changes in other framework conditions (Taylor et al., 2012).

2.3 International experiences

Which conditions might have led to a more ambitious and/or more successful development and deployment of electricity storage in non-European countries? Why do we observe active R&D in some places and in others not? Why did developers settle in certain regions? This might have reasons originating in power sector architecture, but also in market design and regulation. In the following, international experiences, namely from the US and Japan, are presented.

2.3.1 Experiences from the US

The US power system faces similar challenges as the European one, including a continuously increasing electricity consumption and some attempts to increase the penetration of renewable energies. As of 2010, 38 States had a renewable portfolio standard or a similar policy goal. This does mirror in an increased need for system flexibility and electricity storage might play an increasingly important role in the future system, too. In addition, the US power system faces substantial congestion problems to be solved and thus, a strong need for grid expansions, which in some cases can be another driver to trigger investment in electricity storage units to avoid (or post-pone) building new lines. Indeed, transmission and distribution deferral is a viable business case for storage operators in the current US power system (Pieper and Rubel, 2010).[11]

To date, pumped hydro with more than 22 GW of installed capacity is by far the most dominant storage technology employed. Another 49 projects with a total capacity of 37 GW have been proposed; however, the combination of high capital cost and long permitting and construction times imposes high risks on investors and it is uncertain, which projects will finally be realized. There is one commercial CAES facility operated by Alabama Electric Corporation in McIntosh, two additional CAES projects are in an advanced development stage. Besides, some non-negligible capacities of different battery systems and other energy storage technologies are in operation. A recent pattern of deployment involved the installation of an initial small capacity unit, typically with some public co-financing, followed by larger deployments with reduced public support (Sioshansi et al., 2012).[12]

Table 3: Installed electricity storage technologies in the US

Technology	Installed capacity (MW)
PHS	22,000
CAES	115
Flywheels	28
Thermal peak shaving (ice storage)	1,000
Li-ion batteries	54
Ni-Cd batteries	26
NaS batteries	18
Others (flow batteries, lead-acid)	10

Source: Electricity Advisory Committee (2011)

The emerging policy framework at the federal level does support both the development and deployment of electricity storage. The US Department of Energy (DoE) has published an 'Energy Storage Program Planning Document' covering the short-term period up to 2015. The DoE here is engaging in providing assistance in three main areas (R&D, demonstration/deployment, and systems analysis) with the overall objective to reduce the cost of energy storage until 2015 by 30%. Public (co) funding coming from organized programs is explicitly targeting RD&D in the area of electricity storage. In particular, DoE fund-

11 American Electric Power, the largest owner of transmission assets and a major US electric utility, has invested in four battery systems (Ohio, West Virginia, Indiana, and Texas). These have a combined capacity of 10 MW. The company intends to substantially increase its storage capacities further in the coming decade (Kaplan, 2009). It also has sent a request to the State regulator to have its Texan storage facility treated as a transmission asset.

12 E.g. the deployment of a 100 kW NaS battery in 2002 by AEP, of a 1 MW unit in 2006, three 2 MW units in 2008 and a 4 MW unit in 2009; or the deployment of a 1 MW Li-ion battery system by AES Corporation in 2008, followed by several projects including a 32 MW facility in 2011.

ing of various storage solutions is supported via the American Reinvestment and Recovery Act (ARRA) (~200mn USD devoted to storage technologies) and the Advanced Research Projects Agency-Energy (ARPA-E; ~520mn USD as of 2011).13

In addition, recent changes in regulation make the electricity storage business case more attractive. And indeed, the most active deployment of batteries and flywheels takes place in restructured markets where storage provides frequency regulation (e.g. a 3 MW flywheel project in New York ISO market or a 1 MW battery in PJM, see Sioshansi et al., 2012). FERC orders 890 and 719 required system operators to modify tariffs and market rules such that non-generation resources can fully participate in established markets alongside traditional generation (EPRI, 2010). In response, ISOs are in various stages of implementing rule changes and pilot projects that allow storage to provide regulation services of 1MW capacity over a time interval of only 15 minutes. Order 755, issued in October 2011, aims to ensure that providers of frequency regulation "receive just and reasonable and not unduly discriminatory or preferential rates". It requires RTOs and ISOs to compensate frequency regulation resources based on the actual service provided, including (a) a capacity payment that includes the marginal unit's opportunity costs and (b) a payment for performance that reflects the quantity of frequency regulation service provided by a resource when the resource is accurately following the dispatch signal. Indeed, energy storage technologies such as flywheels and batteries can often engage and ramp-up faster than conventional technologies used for frequency regulations. This new legislation may lead not only to the recognition of these qualities, but also to reduce regulatory uncertainty faced by industrial players. As such, this change in legislation may encourage both investments in technology RD&D and deployment.

Notwithstanding policy at the federal level, a number of US States are also actively promoting the development or deployment of energy storage technologies – among them, the state of New York through the New York State Energy Research and Development Authority, or the state of Kansas. California includes energy storage in its Integrated Resource Plan and has introduced the Energy Storage Bill in 2010, which requires electrical corporations and local publicly owned electric utilities to procure new energy storage systems that are sufficient to provide specified percentages of the utility's average peak electrical demand using stored energy that was generated during off-peak periods of electrical demand.

2.3.2 Experiences from Japan

Japan has a very particular power industry structure being highly dependent on imports of primary energy sources and a long time, until the Fukushima disaster, the country relied on a large share of inflexible nuclear power in the generation mix (~25%). Renew-

13 ARPA-E seeks to finance creative, "out of the box", transformational, generic energy research that private initiatives by themselves will not support because of high risks involved. In the US, one of the primary obstacles to energy innovation is insufficient private funding in R&D. Private sector energy R&D represented 0.23% of revenues in 2007, whereas the industry average was 2.6% (Weiss and Bonvillian, 2009). ARPA-E funding related to energy storage includes research on lowering reliance on rare earth materials for batteries (REACT), cost-effective thermal energy storage (HEATS), battery storage technologies for transportation (BEEST), cost effective grid-scale storage to facilitate RES integration (GRIDS), etc. As of 2011, universities have benefited from 43% of the 521.7 million USD invested by ARPA-E, while large private firms and small businesses have received 19% and 23%, respectively. As of 2011, ARPA-E projects have also received at least 200 million USD in private investment beyond ARPA-E funding (Wurzelmann, 2012).

able energies also will continue to play an increasing role in the future; a renewables portfolio standard has been adopted in 2004 with a target of 16 TWh to be produced from RES by 2014 (Electricity Review Japan, 2011). Its comparatively strong position in electricity storage development (especially battery systems) has its roots in these framework conditions and the related supply security concerns.

PHS is quite well developed in Japan. In fact, it ranks among those countries that have the highest number of installed PHS units. Installed PHS capacities amount to more than 25 GW, which is the equivalent of about 10% of the country's total generation mix. Besides, also 270 MW of NaS battery systems are in operation.

Table 4: Installed electricity storage technologies in Japan

Technology	Installed capacity (MW)
PHS	25,500
CAES	-
NaS batteries	270
Others	n.a.

Sources: DOE (2012) and Electric Storage Association (2010)

Research in NaS batteries have been pioneered in Japan since 1983 by Tokyo Electric Power Corporation (TEPCO) and NGK Insulators. One of the first projects was undertaken as part of the Japanese Ministry of International Trade and Industry (MITI) "Moonlight Project" (see e.g. Kimura, 2009). The project was dedicated to research on energy efficiency technologies, as a policy response to the oil shock. Today, NaS batteries have been tested and demonstrated in over 190 sites in Japan; the largest being a 34 MW / 245 MWh unit for wind stabilization in northern Japan (Electricity Storage Association, 2010). NGK Insulator has become the market leader for NaS technologies. Today, the New Energy and Industrial Technology Development Organization (NEDO) conducts various activities focusing on R&D related to oil-alternative energy technology, technology for the efficient use of energy, and industrial technology.[14]

The Japanese experience is interesting, in that energy storage technology development does result from a strong industrial policy. Indeed, the initial "Moonlight Project" was not devoted only to develop energy storage technologies, but sought to search for alternative solutions to ensure Japan's energetic independence. TEPCO's project on NaS was among alternative projects that developed under this industrial support. Even today, on examining various projects financed by NEDO, one may remark that the projects seek out a solution to a particular problem, and energy storage technologies benefit from these fundings because they may be part of the solution.

The Fukushima accident had a substantial impact on the country's energy strategy. The government announced to review its Strategic Energy Plan and it is very likely that energy and environmental policies will support the move towards a system with a lower dependency on nuclear power and a higher share of distributed renewable generation. The situation also has stimulated interest in small-scale energy storage systems directly connected to end-consumers to develop resilience at the individual household level to energy supply issues (Taylor et al., 2012).

14 Current NEDO projects related to energy storage include the development of an electric energy storage system for grid-connection with new energy resources, the development of high-performance battery systems for next-generation vehicles, an R&D initiative for scientific innovation of new generation batteries (RISING), or a fundamental study evaluating a method for battery material R&D. Besides, NEDO also finances R&D related to hydrogen storage and fuel cells.

2.4 Guidelines for public support to RD&D

In the following, guidelines for public support policies targeting electricity storage research, development, and demonstration (RD&D) are provided. We first ask whether there is any need for public support. Second, recommendations for an adequate design of support policies are developed, and finally, the need for joint action at supra-national level is discussed.

2.4.1 Need for public support?

Electricity storage has been identified as one key technology priority in the transition of the European power system towards decarbonization in the 2020/2050 context (see e.g. JRC, 2011; EC, 2011). As shown above, the majority of possible technologies is not yet commercially available and substantial RD&D efforts are required to improve their operational characteristics and achieve cost reductions. Technologies lacking any commercial near- or mid-term potential might become highly relevant in the longer term.

Does an adequate portfolio of existing and new storage technologies develop spontaneously? This might not be necessarily true given some specificities of the context. First, there is the problem that without any further support, innovating firms cannot fully appropriate the returns from their research activities due to existing positive externalities. Second, innovations in energy storage technologies often pair very high capital requirements with substantial technical, regulatory and market uncertainties[15], which also might hamper access to finance. Third, there is a tension to resolve between the need to encourage private sector RD&D, which often is argued to require a strong enforcement of intellectual property rights, with the desire to make the resulting discoveries supporting decarbonization as widely available as possible so that they can be deployed at scale.

The presence of market failures and high risks at stake encourage private inventors and investors to focus on projects that pay off in the near-term, whereas the optimal portfolio of flexibility technologies has a considerably longer time horizon – certainly looking ahead to the 2050 target. Hence, public support is necessary to reduce the risks of investment in RD&D and boost the level and timing of private investment and, thus, to speed-up the commercialization of promising energy storage solutions.

2.4.2 Design of public support policies

Market pull instruments are policy measures that trigger market-led technological change and deployment. Market signals can indicate the potential need for new technologies and ideally should incentivize researchers and investors to re-direct their resources to promising new technologies in order to keep (or get) a competitive advantage. Measures include regulatory limitations such as GHG emission caps, standard setting, intellectual property protection, or a smart energy market design (see Chapter 5 for more details and related recommendations). However, these measures mainly stimulate innovation through (actual and expectations of) deployment and the presence of the various market failures

15 These include for instance uncertainties related to the future power system characteristics, such as the level of RES penetration, the share of inflexible base-load technologies, the carbon price, the role of demand side measures in peak shaving energy consumption and provision of system services, etc. The future development and cost evolution of alternative means of flexibility and innovations in complementary areas, such as ICT, smart grid technologies or power electronics, will impact the future business case of storage technologies, too

discussed above probably would lead to sub-optimal RD&D expenditures in the absence of further direct public support (i.e. technology push) measures.

There is a consensus in energy technology policy literature that market pull alone typically does not lead to the desired outcomes (see e.g. Norberg-Bohm, 1999; Horbach, 2007; Nemet, 2009). The relative importance of market pull to technology push decreases as one moves from technologies close to market competitiveness towards highly immature ones that might have to play an important role in the future system (Grubb et al., 2002; Grubb, 2004). Hence, the transition to a low-carbon and at the same time still high-reliability power system, conducted at minimal social cost, will involve direct public support to innovation in energy storage, too. Available instruments mobilizing public funds include public loans and loan guarantees, public equity investment and subsidies. In a former THINK report (Olmos et al., 2011), we developed guidelines on the optimal design of direct public support to innovation:

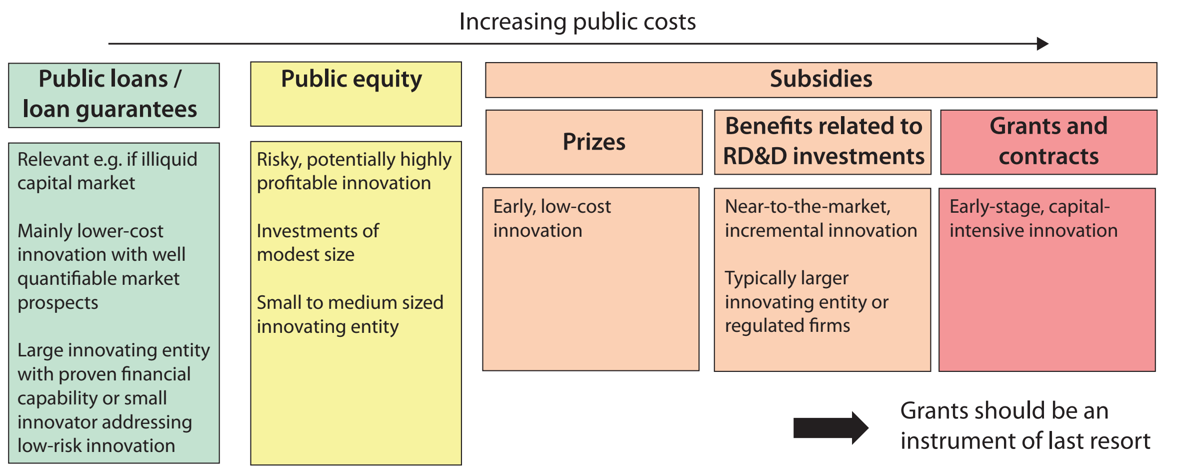
First, the form of support needs to be tailored to the features of each innovation project and to the type of entity best placed to undertake the respective RD&D. The aim should be to maximize the amount of RD&D subject to public sector's funding by leveraging private sector funding as far as possible (see Box 3). Second, competition for funds whenever feasible will set incentives for high efficiency in RD&D. The public sector should avoid identifying 'winning technological options' and instead should leave these decisions to the industry. Third, public funding should be (especially for technologies of higher technological maturity) output-driven, which involves that the release of funds and their amount is made conditional on performance. And finally, the institutions set up to allocate funds to RD&D projects should be lean and flexible enough to avoid institutional inertia and lock-in, which make it hard to reallocate funds when it becomes clear that the original projects turned out to be less promising than expected.

There are some interesting examples where the development of electricity storage technologies has been pushed without simply providing public funds in the form of grants to single projects. For instance, the US Storage Technology of Renewable and Green Energy Act issued in 2009 extends *investment tax credits* to electricity storage. An *EIB loan* (€300mn) has been awarded to Energias de Portugal for upgrading the Alqueva and Venda Nova PHS plants and also the PHS facility in Luxembourg has been financed using (besides equity and private loans) EIB and KfW loans. The UK Low Carbon Network Fund supports 'flagship projects' sponsored by DNOs, among them also projects including storage solutions. Money for these so-called 'Tier 2 projects' is allocated based on an annual *competition*. The German *"Speicheroffensive"* announced in 2011 improves the conditions of electricity storage in the market via an exemption from grid tariffs (market pull) and at the same time, RD&D is planned to be supported via an interdisciplinary and coordinated research program including demonstration facilities and in a "storage roadmap"; the need, technological development, and strategy for public support and framework conditions will be investigated (technology push). About €200mn have been made available until 2014 to (co-)finance research in the framework of the "Förderinitiative Energiespeicher".

2.4.3 Need for EU involvement?

Alternative forms of EU involvement have been addressed previously by the THINK Reports #4 and #6 (Meeus et al., 2011; Ruester et al., 2012). They are based on the understanding that the move of regulatory power from a lower to a higher federal level (from national to trans-national or even the European level) has ben-

Box 3: Supporting RD&D – No grants for all



Source: Olmos et al. (2011)

Public loans are well suited to finance lower cost innovations with well quantifiable future market prospects carried out by large companies. They become relevant if the liquidity of the capital market is low or if the innovation targeted is related to activities where the public sector is more experienced. Public loans are also attractive in recessions when private credit markets' appetite for risk is depressed. *Public equity* is suitable to finance risky, potentially highly profitable, innovation preferably undertaken by small entities. These investments should be of modest size, though they may be used to marginally fund expensive innovation to signal that it has a high potential.

Subsidies in the form of *technology prizes* shall fund early low-cost innovation preferably undertaken by universities and research institutes. *Tax credits and other benefits related to RD&D investments* are best suited to support near-market, incremental innovation conducted by large companies, as well as to innovation conducted within regulated entities.

Grants and contracts – on the one hand the most attractive form of support from the innovators' perspec-tive but on the other the most expensive instrument – should only be awarded to socially desirable clean energy innovation that would not be undertaken otherwise and where all other instruments would fail. This is clearly the case for most early-stage, capital-intensive processes as well as for many other pre-deployment RD&D activities. They may also be especially relevant to support innovation in regulated entities.

efits and costs.[16] The challenges we face, i.e. those accompanying the transition to a low-carbon, high-reliability power system at acceptable social costs, are clearly European and individual MS action is likely to lead to a sub-optimal outcome. It is thus legitimate to look at this more closely to investigate whether there are substantial economic benefits to be made from a renewed EU involvement regarding the development and deployment of electricity storage. Chapters 4 and 5 present viable future business models for electricity storage and provide recommendations for adaptations in market design and regulation, addressing also the question of possible EU involvement in these areas. The following discussion focuses on direct public support to innovation.

16 Any EU involvement must not go beyond what is necessary to achieve the high-level objectives in the EU Treaties, except for areas of EU exclusive competences. EU action shall only be taken when it is more effective than actions at national, regional, or local level and the principle of subsidiarity holds. Benefits may result in the convergence of national policies and, thus, to overall economic benefits that can be shared, transnational externalities can be internalized and thus treated more efficiently, and network benefits be reaped that might not have been realized by national policies. Potential disadvantages are the disregard of national specifics, the reduction of institutional competition between alternative policy approaches, and the loss of decentralized "participatory energy".

Although the EU's contribution to energy RD&D is modest (see EC, 2009) it can play a number of important roles. In particular, EU funding can encourage a coordinated increase in Member State's research in promising areas; support high risk, high cost, long-term programs that would be challenging even for the larger Member States; encourage cross-border partnerships to transfer skills from stronger to weaker partners; play a strategic role in rebalancing the portfolio of projects to offset any tendency that Member States might have to concentrate on a subset of more immediately prospective innovations; encourage the wider dissemination of RD&D; and, finally, may create a more credible future funding environment by requiring joint agreements that take precedence over domestic funding allocations.

Financial support to RD&D in energy storage technologies already takes place both in a decentralized manner on a Member State level as well as via a centralized distribution of EU and pooled Member State funds. However, support programs are hardly coordinated – neither between different Member States, nor between them and the EU. This restricts knowledge sharing, increases the likelihood of costly duplication of similar research and fails to exploit potential benefits from economies of scale and scope via a pooling of resources and active networking. The European energy technology policy instrument in place, namely the Strategic Energy Technology (SET) Plan launched in 2008, is built on technology roadmaps where action plans covering the decade 2010-2020 for nine sectors have been developed (EC, 2009b).[17] Electricity storage so far is recognized as a key technology in the European electricity grid initiative and as a complementary technology for solar CSP. A Joint Programme on Energy Storage has been launched in November 2011, in which partners from 12 Member States will work together with the aim to align their RD&D activities within five sub-programs (i.e. electrochemical- chemical-, thermal-, mechanical-, and SME storage).

However, as discussed above, there is no clear vision on the future role of electricity storage in the European power system. A broad spectrum of technologies, including bulk large-scale storage such as PHS, smaller-scale storage such as battery systems, but also thermal storage directly connected to end-consumers or solar power plants, might be used in a broad range of applications. It has to be stressed again that it will make a difference whether we move towards 'European-wide energy superhighways', or whether we move instead towards a system in which a further increased penetration of small-scale distributed generation and successful demand side management reflect in rising local energy autonomy.

A renewed European energy technology policy, going beyond the SET-Plan horizon of 2020, should include a technology roadmap for electricity storage. Coordination among Member State and EU support policies have to be improved and public support should target a balanced portfolio of identified key technologies, including both centralized and decentralized energy storage technologies. It should consider an extended timeframe up to 2050 with intermediate milestones for 2020, 2030 and 2040, thus include also highly immature but probably promising technological options. Areas where European players already have a strong position in RD&D and/or manufacturing and which have potential for future growth should be of particular interest.

17 So called "European Industrial Initiatives" bring together industry, academia, Member States and the EC with the aim to develop low-carbon technologies. Initiatives target solar, wind, bioenergy, fuel cells and hydrogen, smart cities, electricity grids, CCS, and nuclear fission and fusion. For more details see http://setis.ec.europa.eu.

Besides, an improved communication is of utmost importance, too. This could involve for instance a knowledge pool collecting information on installed capacities of various technologies (commercial but also pilot and demonstration facilities) in different Member States, or the exchange of information regarding functioning practice of 'real-world' pilot projects. The European Association for Storage of Energy should take an active role here.

3. The economics of electricity storage: Viable business models

After an introduction of what is meant by 'electricity storage business model', this chapter gives an overview on the current market design and regulatory aspects relevant for electricity storage, studies selected existing projects, and provides a general analytical framework for viable business models for electricity storage in the future power system.

3.1 The electricity storage business model

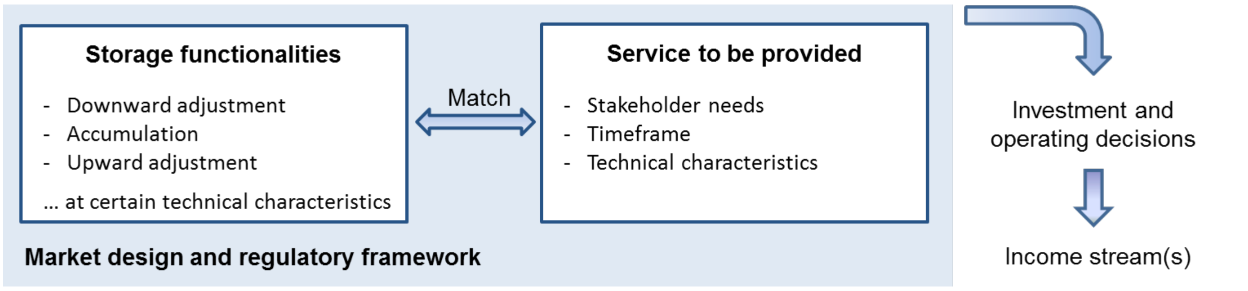
The business model refers to the way the business creates value. The core of the business model for electricity storage is how the storage facility's functionalities (regarding (1) downward adjustment, (2) accumulation and (3) upward adjustment – at specific technical parameters) are matched with services to be provided (regarding stakeholder needs, timeframe, and technical parameters).[18] A business model concept depends on market design and regulatory framework. Investment and operating decisions as well as income stream(s) are determined by the way storage is supposed to be used, as illustrated in Figure 8. Hence, the way storage is used is the core of the business model of storage.

Numerous studies have been undertaken to assess the value of specific uses of storage. Some focus on the arbitrage value of electricity storage in the electricity spot market (e.g. Lund et al., 2009; Muche, 2009; Sioshansi et al., 2009, 2010). Walawalkar et al. (2007) estimate the value of electricity storage when providing primary regulation services. Other studies assess the use of storage to optimize the generation portfolio (e.g. Brown, 2004; Crampes and Moreaux, 2009; Yiannis and Emmanuel, 2007) or look into the use at transmission or distribution level (Delille et al., 2009; EPRI, 2006, 2007; Sandia National Laboratories, 2005, 2007; Silva et al., 2008). End-user applications are typically studied in the scope of distributed energy storage systems. The economics of coupling electricity storage to wind farms is investigated in Black and Strbac (2006), Dufo-López et al. (2009), Duque et al. (2011), Fertig and Apt (2011), Kapsali and Kaldelli (2010), Korpaas et al. (2003), or Lipman et al. (2005). An overlap of the two former categories of studies is discussed in Denholm and Sioshansi (2009) and EPRI (2004), which deal with the transmission-related benefits of combining wind and storage.

However, most of the analyses mentioned above cannot show profitability of storage by providing only one specific service in the current market context. But this does not necessarily imply that electricity storage

18 Several technical and commercial criteria besides energy rating, power rating and response time will be relevant for selecting the most suitable technology. For instance, energy and power density (i.e. the available energy and maximum power per liter or per kg) is an important figure for many – especially mobile – applications. Auxiliary components (e.g. ICT components for monitoring, control and remote control) will determine the total system costs and are often independent of system size. Therefore, a storage system might only be economically attractive above a certain minimum energy and/or power rating.

Figure 8: Illustration of the electricity storage business model



Source: Own depiction

is not an economic business or valuable solution for the power system. To reveal the overall value of storage for the whole system, it is necessary to investigate the way to aggregate the benefits of storage for different services or even different actors that encompass both regulated and competitive activities. Today' challenges for the business model for electricity storage are (i) the **aggregation of multiple services** and (ii) the **maximization of multi-income streams** (see e.g. Sandia National Laboratories, 2005; Walawalkar and Apt, 2008; Delille, 2010; He et al., 2011).

Referring to Figure 8, there are endogenous choices and exogenous factors that affect the viability of the business model. The former refers to finding the optimal match between functionalities and services, which are the target services of the storage unit. The latter refers to market design and regulatory framework which will have an impact on whether the services which electricity storage does provide to the system or individual stakeholders are adequately rewarded acknowledging their value.

3.2 Context: Current market design and regulatory framework

A market typically is considered as an efficient mechanism to discover value and to organize transactions. But it is not the only available mechanism. In some cases there are good economic reasons for the absence of a market (e.g. specificity of the underlined good and high ex-post transaction costs of market exchange). Furthermore, the birth of a market might need a certain push accompanied by a restructuring of the industry, as seen in the past with the liberalization of e.g. European telecommunication and power sectors. In the following, the current design of the markets for services that electricity storage can provide and regulatory aspects determining the deployment and operation of storage are presented.

3.2.1 The markets for services that electricity storage can provide

The viability of a certain business model is directly related to the value of market prices. The *availability* of market prices is a precondition to conceive relevant business models, and the *credibility* of market prices affects the credibility of the result of the business model. Therefore, we examine in the following whether the current market design of the European power system does provide the necessary and credible signals. For each service that storage could provide, possible market absence and market failures are identified. It is then analyzed if a possible market absence is justified and if market failures might already be (partially) corrected by existing regulation (Table 5).

Energy markets

The credibility of the spot price cannot be evaluated by focusing only on the underlined market and without assessing the interaction with other markets. Therefore, spot and balancing markets are analyzed jointly, as the transacted products are both energy, only differing in time horizon between settlement and delivery. In fact, the price signals of the balancing markets could – to a certain extent – account for the price depression in the day-ahead spot market. The logic is simple: if it is cheaper to buy power near real-time, there is no incentive to buy at a higher price day-ahead. There are two main reasons that could account for a price depression in balancing markets, namely ad-hoc peak load arrangements, and the price fixation method in balancing markets. Another default which should also be improved is the lack of liquidity.

Ad-hoc peak load arrangements refer to some kind of ex-ante capacity payment for peak load units, which enables them to bid into the energy market at a lower price. Such arrangements, though implicit, are quite common. The Norwegian TSO Statnett implemented a reserves option market to secure sufficient resource bidding into the balancing market. Similar practices

Table 5: Services storage can provide and their markets

Service	Source of remuneration	Are there market failures or even market absence?	Regulatory intervention in place
A. Price arbitrage (at different time horizons)	Wholesale market	Possible market failures are related to the reliability of price signals: 1. Low demand elasticity 2. Market power 3. Market design in terms of price cap/floor 4. Ad hoc peak-load arrangement	Market power monitor and move to an internal market (correct A2) Several power exchanges introduced negative prices (correct A3)
B. Demand response / time shifting of demand	End-user pricing	Market absence for residential market bc of: 1. Often absence of time-varying prices 2. Low short-term price elasticity Some countries have even regulated end-consumer prices (causing partly B1 &B2) Situation better for industrial consumers (in some cases time-varying prices employed, higher demand elasticity)	Directive 2006/32/EC mandating installation of smart meters (partly correct B1) as well as informative billing (partly correct B2) (also confirmed in the recent proposal for a new energy efficiency directive)
C. Extra high end-user power quality / autonomy	Private valuation	Absence of market bc of: Subjective evaluation of 'power quality' (high specificity of the underlined service). If a party (like a manufacturing company, an internet service provider or a hospital) values supply security and/or power quality very high, private benefits will exceed costs à cost of not delivering electricity at desired quality level here justifies sophisticated and costly solutions	

D. Balancing services	Balancing market	Possible market failures are related to the reliability of price signals: 1. Access barriers: minimum bidding volume, minimum bid duration, binding up/down bids requirement, etc. 2. Liquidity and competition: partially related to the access barriers which limit the potential players + high concentration of suppliers in whole-sale market also mirrors in balancing market + single buyer of balancing services in some countries (one-side market) 3. Externality: independent and heterogeneous balancing markets in a physically connected European power system, necessarily giving rise to spillover of flexibility resources over the borders 4. Market design in terms of price cap/floor	Transparent and non-discriminatory nature of dispatching and balancing: D2009/72/EC Art. 15 (partly correct D2) Balancing market integration will be subject of a FG to be developed by ACER (correct D3, partially correct D2) Collaboration initiatives between neighboring TSOs to exchange the balancing resource 19 (correct D3) Several power exchanges introduced negative prices (correct D4)
E. Primary frequency control	Mandatory provision (ES) Bilateral contract (FR) Tendering (DE, UK, SE)	Market absence can be justified bc: Service is intrinsically homogeneous over the geographical area	
F. Secondary frequency control	Bilateral contract (FR) Tendering (DE) Spot market (ES)	Market absence can be justified bc: Service is very location-specific	
G. Voltage control	Mandatory for basic V-control (ES, DE, FR, UK, SE) Bilateral contract (FR, DE) Tendering (UK, ES)	Market absence can be justified bc: Local task, using local resource to resolve local problems, so highly susceptible to the exercise of market power Kind of 'byproduct' à difficult (or even impossible) to measure cost of service provision	
H. Blackstart	Bilateral contract	1. Market absence; few eligible providers of such service 2. Heterogeneity of the remuneration scheme among MS	No remuneration in some countries Procurement could be integrated in grid connection agreement (correct HI)
I. Congestion relief	Bilateral contract Open season tendering	Tendering process assimilating market arrangement, but possible failure related to 1. Access barriers regarding the congestion management service requirement: minimum functioning time and performance, etc.	Authorization of grid operators to acquire necessary sources (be grid, supply or demand side) to relieve congestion (further clarification could help to correct I1)
J. Connection of generators and load		Market absence for both (a) RES-connected storage and (b) grid connected storage 1. Feed-in tariff and/or (partial) exoneration of imbalances for renewables 2. Connection of generators and load defined as regulated based activity	Foreseen termination of FITs in some countries (correct J1) DE: Recent change in EEG favors domestic use of distributed generation (correct J1) Debate on the classification of storage as grid asset; Italian initiative to allow TSOs to build and manage 'diffused' storage systems (related to J2)

19 For instance, the French and British TSOs have signed a Balancing and Ancillary Services Agreement which allows them to exchange power over their Interconnector. This agreement provides access for both system operators to the residual capacity of the interconnector to manage constraints or for energy balancing purposes on their system.

can be found in France, where RTE remunerates a capacity payment for fast tertiary reserve to bid into the balancing mechanism. Practices of other Member States are summarized in Table 9 in Annex 2.

The *price fixation methods used in balancing markets* vary from country to country (Eurelectric, 2004; Vandezande, 2011). It is common that bids are selected according to the merit order of the bidding prices; however, it is not in every balancing market that the selected bids are remunerated with the marginal price. Balancing energy instead may be remunerated based on pay-as-bid (e.g. Austria, Italy) or at average prices (e.g. France, Germany, or the UK). For more details see Annex 2.

Furthermore, there is generally a *lack of liquidity* of the balancing market. This is partially reflected in the concerns of TSOs to secure sufficient bids. Other more inherent reasons are the small scale of this market (only several hundreds of MWh transacted per hour), the limited number of market participants, and restrictive bidding requirements.

In addition, *administratively fixed price caps and floors* in many power exchanges have been widely criticized as another reason for spot price depression. While the effect of price caps on price depression certainly exists, it could be exaggerated[20], giving other important reasons which could be the ad-hoc peak load arrangements and the depressed price on the real-time market. Negative prices are gradually permitted in different markets, reflecting the system's need for downward adjustments.

Low (short-term) demand elasticity can also affect the credibility of the energy market price, but one should note that higher demand elasticity should result in a further reduced contingency pricing, lower price volatility as well as a possibly lower peak price level. While apparently the storage's business could be negatively correlated with enhanced demand elasticity, it should also be noted that storage is an important enabler of demand elasticity without compromising the quality of comfort or productivity associated with the power consumption. The rollout of smart meters, the introduction of time-varying consumer prices also for smaller-scale commercial and residential customers, and the use of informative billing are prerequisites for using demand side potentials and to integrate storage into demand side management (see also Olmos et al., 2011b). The implementation of Directive 2006/32/EC will accelerate this process.

Ancillary service markets

The proper functioning of electric power systems depends on two basic requirements: first, generation and load have to be balanced at every moment in time; and second, power flows need to be managed within the constraints of the individual transmission facilities. A legal definition of ancillary services, together with a definition of underlying principles according to which their provision should be organized, is given in the Electricity Directive.[21] Thus, there is considerable functional similarity regarding the provision of ancillary services across

20 It should also be noted that a price cap is rarely attained (Hirschhausen, 2012). Price caps amount to 2000 to 3000 €/MWh in most of the European power exchanges (see Annex 2). One could argue that they are still below the VOLL (value of lost load), but the fact is that such contingency pricing only happens during very few hours per year. In most of the time, the price cap does not cap.

21 Directive 2009/72/EC, Art. 2 (17): "[…] 'ancillary service' means a service necessary for the operation of a transmission or distribution system." The ENTSO-E Operation Handbook defines ancillary services as "interconnected operations services identified as necessary to affect a transfer of electricity between purchasing and selling entities (transmission) and which a provider of transmission services must include in an open access transmission tariff".

markets. However, wide heterogeneity exists regarding the (stage of and way of) implementation of this Directive and a low degree of compatibility of market designs has been achieved so far (see also Kapetanovic et al., 2008; KU Leuven and Tractebel, 2009).

As summarized in Table 5, several forms of procurement and remuneration co-exist, including mandatory provision, bilateral contracts, tendering or the use of the spot market. All options have pros and cons and the suitability of one option depends on the service targeted. Ancillary services like primary and secondary control, voltage support, or black start are traditionally procured by the TSO on a regulated basis. This is in line with the consensus that the solution to short-run supply security does require a centralized management (Roques, 2008). This centralized management does not conflict, in principle, with a market-based approach of ancillary services; and as indicated by Heffner et al. (2007), who provide an interesting study comparing selected European and non-European ancillary service markets, there is a clear trend towards market-based procurement for ancillary services which probably will lead to cost savings.

Capacity mechanisms

A capacity mechanism currently is extensively debated in several European countries (Germany, France, Spain, Italy, etc.). The call for such an instrument is mainly based on the risk of long-term under-investment in generation capacity, especially peak power plants. However, there is no consensus yet regarding many key issues related to necessity and design of such mechanisms.

3.2.2 Complementary regulatory aspects

A first relevant regulatory aspect is the classification of the storage assets as generator and/or load, depending on the mode of operation. This has implications for the technical issue of grid connection as well as for economic issues such as the eligibility to grid tariffs, or the ownership of storage assets, where a debate appears given that on the one hand the principle of unbundling holds, but on the other hand regulated actors might ask for controlling electricity storage devices given their mission to "keep the lights on".

Directive 2009/28/EC, furthermore, does explicitly refer to storage. Accordingly, "Member States shall take appropriate steps to develop transmission and distribution grid infrastructure, intelligent networks, *storage facilities* and the electricity system, in order to allow the secure operation of the electricity system as it accommodates the further development of electricity production from renewable energy sources […]" (Art. 16). However, neither the proposed Infrastructure Package, nor the Ten-Year-Network-Development-Plan published by ENTSO-E include a clear and comprehensive vision on the future role of electricity storage. Both only refer to large-scale bulk storage connected to the transmission grid. Neither small-scale storage associated to the distribution level or end-consumers, nor hybrid projects combining RES and storage assets are considered. However, as discussed above, the future power system might move towards decentralized solutions and rising local energy autonomy, featured also by widespread demand side management, which probably would substantially reduce the need for centralized storage solutions.

It also has to be noted that some recent Member State initiatives regarding the regulation of electricity storage are quite heterogeneous. For instance, since late 2011, Germany exempts new electricity storage facilities (and PHS expansion projects) for a defined period of time from grid tariffs. A recent change in Italian legislation allows the TSO to build and manage 'diffused' storage systems such as batteries. This diversity in national regulatory practices regarding for instance the eligibility to grid tariffs could lead to a suboptimal distribution and allocation of storage resources on the European level, and also could create some competition concerns. These issues will be discussed in Chapter 5.

3.3 International case studies of electricity storage projects

CAES facility in Huntdorf, Germany

In Huntdorf, Germany, the world's first compressed air energy storage facility, today operated by E.ON, started operation in 1978. At this time, it has been constructed to charge the reservoir during off-peak periods by taking-off the surplus electricity generated at a nearby nuclear power plant and to discharge during peak periods. Hence, major benefits were intended to originate from price arbitrage in the wholesale market. In addition, the storage facility could provide emergency power supply to the nuclear power plant in case of a system blackout. In the 1990s the framework conditions changed (Chapter 2.2), the business case for this storage facility became less attractive and the operator even thought of shutting it down.

The liberalization process and increasing penetration of intermittent renewable energy sources mirrored in an increase in electricity price volatility and an increased need for system flexibility, which generated new business opportunities. This is further supported by the CAES facility's capability to start, stop, load and unload within shorter time periods than most conventional thermal power plants (it does reach 50% of its rated capacity within 3 minutes and 100% within 10 minutes). Turbine capacity in 2006 has been expanded from 290 to 320 MW. The plant runs on a daily cycle, charging the air storage for up to 8 hours and providing generation for up to 4 hours. It is now used as a peak-load power plant providing minute reserve (regulated) and peak shaving (competitive). Recently, the plant has been successfully leveling the variable power from numerous wind turbine generators (EPRI, 2006).

Waldeck PHS expansion, Germany

In Germany, pumped hydro storage can participate in two markets, the spot market for energy and the reserve market (primary, secondary and minute reserve). Moreover, if the PHS plant is operated within a power plant portfolio, it can create additional synergies for the whole portfolio in both markets. The synergy potential is derived from relaxing the various technical restrictions (ramping rate, minimum up/down time, partial load efficiency, etc.) of the different power plant technologies for providing products in the spot and reserve market. They constitute the main drivers for the expansion project of the Waldeck PHS facility, undertaken by E.ON Wasserkraft GmbH in 2012 and adding 300 MW production capacity to the existing 600 MW, which started operation in 1932/1974.

The business model of the PHS plant can be labeled as generation portfolio optimization. Revenue streams come from arbitrage in the wholesale market, capacity payments and revenues from reserve markets, and cost reduction for the overall power plant portfolio. Challenges from the investor's point of view are twofold. First, it includes finding the optimal scale of expansion, considering its use on both spot and reserve market. Second, it includes finding the optimal split of the storage capacity between spot and reserve market depending on prevailing market prices.

Planned storage park Orkney Islands, Scotland

Scottish & Southern Energy Power Distribution (SSEPD) launches a tender process to procure two energy storage systems with two energy storage providers (ESPs), with the aim to solve local network constraints and to search for viable business models. SSEPD already has experience in installing and operating battery storage devices as substation support on a regulated basis. In the UK, the ownership of storage devices by network operators is restricted to date to the island/isolated power systems. This tender represents an endeavor to search for economic viability of storage solutions on a market basis. The project has been co-funded via the Low Carbon Networks Fund.

The business model in this initiative will involve a third party energy storage provider delivering congestion management services to the DNO. The ESP can further benefit from other commercial activities, such as ancillary services contracted with National Grid, or some arbitrage (arbitrage profits at distribution level refer more to peak/off-peak arbitrage than to hourly arbitrage on the spot market, which, however, could be realized through an aggregator). It is a regulated-driven business model without ownership by the regulated actor. The novelty is that in the tender, there is no specification of storage technology, dimension or eligible actor, but only a specification of service requirements. Congestion management requirement, as well as demand forecast and grid expansion plan for the next years are communicated to the bidders.

Electricity storage in island systems

Island systems can provide an interesting business case for electricity storage, especially if they have an ambitious energy policy building on a strong role of renewables. The isolated nature of the power systems imposes technical restrictions on the penetration of highly variable and non-dispatchable RES and there is a lack of a market for the provision of regulation services. Complementary means of flexibility within these systems are key enablers for decarbonization. Existing cases of storage deployment are very heterogeneous. They differ regarding stakeholders involved, applied regulatory rules, and targeted business models. Two cases are presented:

At **La Réunion**, EDF SEI in 2010 installed an NaS battery with a capacity of 1MW/7.2h as a means of storing intermittent energy from a network of PV modules. As an insular system, the power system is exempted from EU Directives. There is no forward- or centralized real-time power market and EDF SEI operates as a vertically integrated utility to produce, transmit and distribute electricity. Benefits from the storage system are derived essentially from peak shaving and ancillary service provision. There are some fringe producers of electricity, who are mainly focused on RES and whose generation is supported through a feed-in tariff system. Third party access to the network is regulated and charges need to be paid. This has an impact on the profitability of storage facilities. Nevertheless, generators benefit from a reduction (40% less than tariffs in France Metropolitan area) when they access the medium-voltage grid. The main challenge for developing further storage at La Réunion stems from the absence of locational signals to guide storage investment decisions.

Box 4: Operation of PHS in different Member States

Most of the existing pumped hydro storage plants were built in the vertically integrated power systems featured by weak interconnection capacities. PHS facilities are typically owned and dispatched by deregulated actors. Their operation today is mainly based on price signals in wholesale markets, with additional revenues being generated from the provision of system services. Diversity in national power mixes, market design, and regulatory frameworks reflects in diversity in the operation of PHS, too.

In France, as in other European countries, PHS participates in day-ahead and balancing markets. Additional earnings through the mechanism of capacity obligation (NOME law) are expected from 2016 onwards. The provision of system services is remunerated based on regulated prices, including primary/secondary frequency control (only turbine mode), voltage control and black start (both turbine and pumping mode). One should note that the controllability of PHS in pumping mode is limited with the traditional synchronous machines, which leaves room for future improvements in flexibility, for instance by using variable speed hydro generators. Regarding grid tarification, PHS is treated as load. A posteriori average value of the grid tariff is about 5 €/MWh. Another important issue are taxes. They account for roughly 45% of the O&M cost of an existing PHS.

The situation in Germany is similar. PHS units participate in day-ahead markets and provide secondary frequency control. Voltage control and blackstart capabilities are remunerated at a regulated price. Capacity payments do not exist. Regarding grid tarification, existing PHS facilities are treated as load and thus pay the full L-charge. New PHS plants and expansions, in contrast, will be exempted from grid tariffs for a certain period of time. It is interesting to note that representatives of German, Austrian and Swiss ministries signed an agreement in May 2012 to further expand PHS capacities and related grids to jointly address the challenges in the 2020/2050 context.

Also in Belgium, PHS units do not receive any capacity payment. Besides price arbitrage, they can provide primary/secondary frequency control (only turbine mode), congestion relief and black start. Voltage control and congestion relief are remunerated based on regulated prices. Regarding grid tarification, PHS pays both L- and G-charges. The G-charge has been introduced on 1 January 2012 (3.1304 €/kW/year + 0.3204 €/kW/month + 1.3 €/MWh). PHS is considered as end user – specific surcharges have to be paid (contribution for offshore wind, federal contribution…). Overall grid access costs amount to 13.5-26.5 €/MWh.

In Spain, PHS receives a capacity payment of 20,000 €/MW for the first 10 years. Yet it has been shown that relying on energy arbitrage only would not allow any green-field PHS to recover the fixed costs (Alba, 2011). Regarding grid tarification, PHS facilities are subject to a G-charge (generation_tax * [generated_energy + 0.7 * pumped_energy])

In **Gran Canaria**, energy storage is treated as a generation facility, and the EU Directives fully apply (unbundling, liberalized supply, free entry in generation). Storage facilities are remunerated through regulated capacity payments taking into account investment and fixed O&M costs, and energy payments based on a fuel price index and variable O&M cost. This leads to a business model for storage based on regulated remuneration. A PHS facility with a capacity of 200MW/311MW is currently developed by Endesa. The investor's main challenge is to achieve the long-term aim of the project, i.e. to make the system evolve towards a hybrid hydro-wind power system.

3.4 Viable business models for electricity storage in the future power system

The general analytical framework for viable business models for electricity storage in the future power system proposed builds on two categorizations:

(1) First, we *categorize storage by its location*, distinguishing between:

- Large-scale storage, connected directly to the transmission grid,
- Small-scale storage, connected directly to the distribution grid or end consumers, and

- Storage facilities being part of an RES-based generation project.

(2) Second, we *categorize the business model by the nature of the main target service*, distinguishing between:

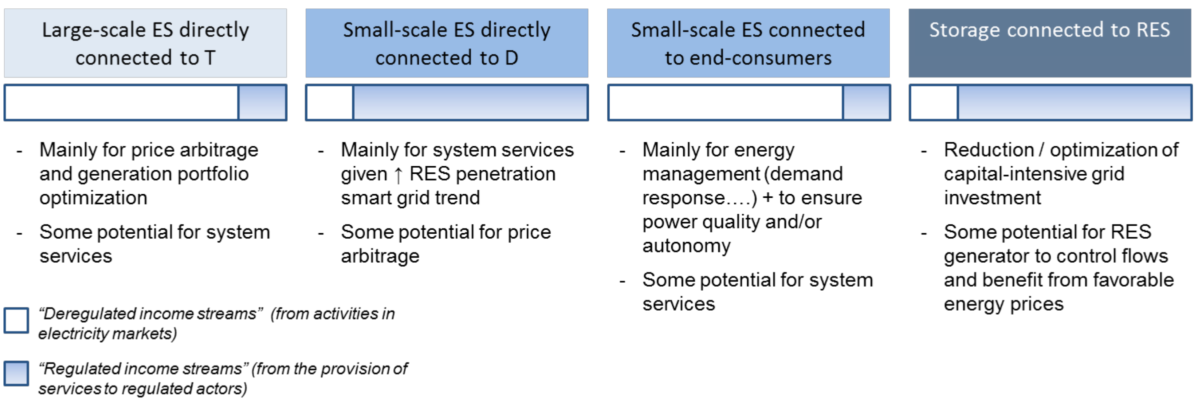
- Deregulated-driven business model (major part of the income originating from activities in electricity markets – "deregulated income streams"), and

- Regulated-driven business model (major part of the income originating from offering services to regulated actors with the procurement being realized via mandatory code or bilateral contracts, i.e. the price information is not accessible by third parties – "regulated income streams").

We differentiate electricity storage by its location because the location will involve different stakeholders. It preconditions combinations of most valuable services and determines the shares of income streams originating from competitive activities on the one hand, or from the provision of services of which a regulated actor is the sole buyer on the other. The location of electricity storage in the power system, thus, is critical to determine the viable business models (Figure 9). One can reasonably anticipate that appropriate incentives and the need for regulatory intervention are different, too.

The case studies presented above confirm that business models vary according to the location of the storage facility within the system, with Huntorf CAES and Waldeck PHS falling into the category of "large-scale storage directly connected to T", the planned storage park in Orkney Island into "small-scale storage directly connected to D", and different island systems into "storage connected to RES". However, Figure 9 should be considered as indicating only a general framework for the most plausible types of business models, while not excluding the possibility of an inversed share of regulated and deregulated income streams for storage at a certain location under specific market and regulatory circumstances. For instance, it is possible that a bulk storage could be primarily used to alleviate a severe and systematic congestion in the transmission network to give time for the line to be built. The same can be true for storage connected to a larger-scale RES generator, or for "prosumers", i.e. actors being both producer and con-

Figure 9: Location of storage against the most plausible type of business model today



Source: Own depiction

sumer depending on time. If the regulatory framework regarding the responsibility of RES firming is shifted to the deregulated actors, the business model would change accordingly. Special premium feed-in-tariffs for renewables that provide firm power when needed could set incentives to take storage devices as part of the business model into consideration. Similarly, support schemes favoring direct consumption of distributed generation will shift demand to those hours where e.g. a PV device is producing and thus could reduce the impact of consumer on the grid, and besides, set incentives to invest in e.g. thermal storage.

Deregulated-driven business model

Electricity storage in its prevailing function here is used for competitive activities and remaining capacities might be used to provide services to regulated actors. The advantage of this model is that storage can provide regulated services without interfering with competition in competitive domains. The main concern is that the prevailing service is subject to many economic uncertainties, which results in an uncertain main revenue stream.

The major economic uncertainty is the evolution of market prices during the lifetime of the storage asset. The profit of the deregulated arbitrage activity strongly depends on the price spread, which decides both "cost" and "revenue" of the energy transacted in the markets. However, the price spread is influenced by many exogenous economic and regulatory factors such as fuel prices, power mix, weather conditions, and ad hoc policies such as market facilitation for renewables. The fuel prices of the base- and peak-load technologies would be the fundamentals to set the level of the peak-/off-peak spread, whereas the power mix (together with the load profile) would determine the occurrence of this price spread. Market integration of renewables is another sensitive issue as RES often have nearly zero marginal costs and their integration into the marginal price bidding system does inevitably depress the market price. This downward pressure of market prices affects the profitability of all generation means, and the effect is further exacerbated in cases where there are administratively fixed price caps and floors, which means that during peak periods, the price is not allowed to be set at the actual value of lost load if it would exceed the price cap, and during off-peak periods the inflexible base-load might not be allowed to offer negative prices (or prices lower than the price floor).

Moreover, the second step of the deregulated-driven business model, i.e. the valorization of remaining capacities with system operators, is not easy to realize either, as actual arrangements of system service procurement often do neither take into account the relative advantages of storage facilities nor the constraint of storage as an energy-limited source. In addition, the remuneration of these services is not fully market-based, which makes an estimation of the value of storage difficult. Controversies may occur in the method of evaluation (cost-based or opportunity cost based), in performance indicators, in the evaluation of fulfillment, etc.

It has to be noted, that the viability of a similar business model can also strongly differ between alternative technologies. Pumped hydro, for instance, requires high upfront investment cost and furthermore is typically subject to long permitting (about 4 years for feasibility study, licensing, permitting, financing, etc.) and construction times (also about 4 years). Long-term investment security, thus, is a key factor especially for this technology. One also has to differentiate between existing and new storage facilities.

Whereas a business model for new facilities obviously will include initial investment cost, existing assets might benefit from amortized assets.

Regulated-driven business model

In contrast, the regulated-driven business model implies that electricity storage in its prevailing function is used to provide services to regulated actors, and remaining capacities might be used for competitive activities. Regulated sources of revenue are guaranteed, but still a well-founded method of valorization is needed to justify the choice of storage instead of alternative means of flexibility. Mechanisms such as auctions for services, concession licenses, and capacity contracts would be considered as another way to evaluate electricity storage for regulated services, but on the same leveling fields as other competitive means of flexibility. It has been shown (Sioshansi et al., 2009; Walawalkar and Apt, 2008; EPRI, 2010) that some regulated sources of revenue are ranked as the highest revenue sources for electricity storage in US markets. In Europe, it seems that the key supportive argument for the regulated-driven business model, i.e. value quantification, is still missing because of a lack of data and transparent pricing mechanisms for system services. While the deregulated value of storage is easy to estimate with reference to market prices, there is not yet consensus over the method or reference value to evaluate regulated services.

Another issue is how to combine the regulated and deregulated use of storage in an efficient way. In the regulated-driven business model, the regulated actor is supposed to have priority over the storage use. However, one should note that the need for system services is revealed only near real-time delivery, while the operating decision regarding competitive activities are taken more ahead of real-time, i.e. at different gate closures of electricity markets. The priority of the regulated actor would impose probably a guaranteed reservation of a bundled capacity of storage (charge-, energy storage-, and discharge capacity). This might lead to an underutilization of storage, because regarding the horizon of deciding on the usage of storage, grid operators should come at the last place (after forward, day-ahead, and intraday markets).

In summary, the differentiation between the regulated- and deregulated-driven business models may help to better understand what the most valuable services, electricity storage can provide, are, and if the current market design and regulation allow to reveal such values in a fair and credible way. In fact, these business models cannot be credibly assessed or anticipated without putting them into the context of market design and regulatory framework. The business model, in its simplest form, is about the costs (investment and operation costs) and benefits (from both regulated and competitive income sources). The operation of storage not only influences the operational benefits, but also optimal investment decisions. It is linked to the services, and services are linked to market design and regulatory rules. Therefore, in order to anticipate the business model of storage for the future European power system, one has to consider its interactions with (a) energy market, (b) ancillary services markets, and (c) possible capacity mechanisms, the three key components of the market structure. Comments and recommendations will be given on the basis of the analysis of the status quo.

4. Proposals for market design and regulation

The above discussions have shown that the viability of a business model is directly related to whether the services which electricity storage does provide to the system or individual stakeholders are adequately recognized and rewarded acknowledging their value. Credible price signals are key. Market absence might be justified in certain situations (for instance for highly location-specific services that can only be offered by a very limited number of parties). However, knowing that a key challenge for the business model of electricity storage today is the aggregation of multiple services and, thus, the maximization of multi-income streams, one has to ask whether flexibility is appropriately valued. The business models for storage, or any other flexibility mean, if potentially viable, should not be impeded by the market or regulatory hurdles.

In the following, proposals for improving market design are provided, addressing both the evolution of current market rule setting and the emergence of eventual new markets. In the perspective that certain profound improvements in market organization could not be realized without regulatory authorization or push, proposals for possible regulatory intervention are also discussed. It has to be stressed again that the purpose is not to setup a framework distorted in favor of electricity storage. In contrast, market design and regulatory framework should be neutral enough to support a portfolio of flexibility means that is needed to enable decarbonization.

4.1 Market rule setting

Although manufacturing costs and technical parameters are often cited as major barriers to the deployment of electricity storage, there are various non-technical issues hampering its adoption as well. In Chapter 4, major obstacles for an efficient pricing in spot and balancing markets have been identified, including ad-hoc peak load arrangements implemented in some markets, the often observed inconsistence regarding price fixation mechanisms in day-ahead and balancing markets, or restrictive bidding requirements. There is also wide heterogeneity regarding the (stage of and way of) implementation of the 3rd Package and a low degree of compatibility of market designs has been achieved so far. This situation does not only create obstacles for the transition to a single European market, but it might also hamper an efficient participation of 'new' sources of flexibility in ancillary service markets.

In what follows, we elaborate proposals for improvements in market rule setting based on the scrutiny of the status quo as presented in Chapter 4.2. Interactions between different market components (i.e. between the energy market, ancillary service markets and possible capacity mechanisms) are considered, too, since these are obviously of high importance for the credibility of market prices (Stoft, 2002). Many of the non-technical issues that hamper the adoption of storage represent similar hurdles to alternative technologies. Thus, addressing these issues will not only make storage more attractive, but it will also improve the economics of alternative solutions.

Energy markets

First, *ad-hoc peak load arrangements* should be considered when defining "energy-only" markets. Their presence suggests that some capacity payment elements already exist in many, if not all, Member States. Studies on the impact of such a mechanism on the functioning of the energy market as well as on competition among players from different Member States could be useful to gain further insights into the "missing money problem".

Second, the *inconsistence regarding price fixation mechanisms* in day-ahead and balancing markets could result in a misalignment of price signals of these two chaining markets. Average pricing or pay-as-bid remuneration in the balancing market could lead to a depressed level of the cost of purchasing energy at real-time, which would condition the price level in the preceding day-ahead market. Therefore, remuneration in both markets should be harmonized and ensure an economically efficient dispatch.

Third, *liquidity of the balancing market* could be improved by modifying market rules. Traditionally, only the balance responsible entities are allowed to bid into the balancing markets.[22] Minimum bidding units (often 1MWh/h) are much higher than in the spot market (0.1 MWh/h). Furthermore, it is often required that balancing bids are symmetric, i.e. providing a symmetric up- and downward regulation power in case of need. All these have limited market access for small, decentralized market players, active loads and storage operators. The argument for limiting the minimum amount of power for a bid is that many small bids can lead to an inefficient regulation. However, automation of calling for bid activation would remove any disadvantage that small bids might have on the quality of regulation (Pozo, 2011). Market rules, thus, should be modified such that they relax minimum bidding requirements and rules requiring symmetric up- and downward bids in order not to impede market access for small, decentralized market players. This will allow storage and other flexibility means to valorize services they technically can provide, and probably also will have a positive impact on market liquidity.

22 There is some on-going progress in certain Member States allowing market players not being balance responsible themselves but attached to certain balance responsible to propose bids in the balancing markets.

Ancillary services

Several forms of procurement and remuneration co-exist. They all have pros and cons and the suitability of one option depends on the service targeted. Mandatory provision does make sense for essential public services whose benefits are spread evenly amongst all parties involved. Bilateral contracts offer some degree of flexibility with respect to service specification, making the provision of ancillary services more tailored to the system operator's requirement as well as to the provider's ability or convenience. Tendering allows introducing more transparency compared to bilateral contracts and more competition for the provision of the service required. The spot market is an efficient way to procure standardized services or products at lowest costs through sufficient competition. It is clear that the suitability of procurement mechanism depends on the specificity of the underlined service and is conditioned by the number and diversity of the potential providers. Back to Table 5, it is unlikely that voltage control or black start services could be more efficiently procured via market-based arrangements, as they are highly location-specific and can be provided only by a few qualified units.

The difficulty for external investors, especially for those not being incumbent generators, to know the value of storage for providing the ancillary services could partially be due to the lack of data and knowledge about the ancillary services procurement and remuneration. This lack of data and knowledge is sometimes related to the adoption of bilateral contracts not accessible for a third party. In this sense, replacing bilateral contracts by competitive tendering wherever possible could help revealing the value that alternative flexibility means, including storage, can provide (services E, F, I, G). In the conception of tendering, it is also recommended to adopt performance-based (i.e. source-neutral) remuneration schemes. This complies with the system operator's chief target to ensure the security of system operation, and also provides a level-playing field for all flexibility means able to deliver the required services.

Besides, regional markets for ancillary services could also support an optimized procurement and use of ancillary services portfolio across Europe. Certainly, to exchange ancillary services within a certain region, appropriate cross-border transmission capacities need to be available. This has to be coordinated with the forward, day-ahead, and intraday transmission rights. One can reasonably anticipate that the exchange of ancillary services comes after the exchange of balancing reserves across borders. Not every ancillary service could be marketed across the region. For instance, voltage control cannot be traded over large distances, and some other services (such as congestion management) are also location-specific. Nevertheless, in an open and single European market, political borders should not restrict the flow of ancillary services. It is the market that should create its own pliable borders, acknowledging technical and economic aspects.

Capacity mechanisms

On the one hand, the necessity of a capacity mechanism remains to be proven. First, capacity mechanisms are generally not considered as curing the root of the lack of investment incentives (Roques, 2008), which is more closely related to the quality of price signals transmitted by the energy market and the provision of ancillary services. It is believed that more efforts should be spent on improving existing market mechanisms rather than giving simply a compensatory payment to peak units. Second, the necessity of a capacity mechanism also relates to how the capacity adequacy is defined. A European perspective needs to be adopted to review the need for capacity investment. Third, in terms of the design of capacity, various options are available (capacity payment, capacity subscription, reliability options, etc.). It is difficult to find a one-size-fits-all design for all Member States, but heterogeneity in capacity mechanism design and remuneration schemes could distort competition among Member States. After all, an important concern about the capacity mechanism is whether it would jeopardize the price signals of the existing electricity markets and pose impediments towards the internal market building.

One should also be aware that to guarantee the long-term reliability of electricity supply, investments in conventional generation are only one type of possible response. Others include grid expansion, electricity storage and demand response. Again, consensus has not been reached on how to assess the capacity value of these flexible sources, which, however, should be placed on a level-playing field towards the common target of security and reliability of supply. As far as the design of the capacity mechanism does not recognize possible contributions of alternative flexible means (including storage) in the capacity consolidation, the implementation of such a mechanism is likely to further dis-incentivize investments in storage as compared to peak generation units.

4.2 Further aspects of possible regulatory intervention

Some more profound market design improvement or progress could not be realized without regulatory authorization or push. Regulation should aim at fostering market access and market build-up, as well as at establishing a level-playing field for alternative means of flexibility. It has to be reminded again that the objective of this report is not to explicitly promote electricity storage but instead to build a neutral frame that does acknowledge the value of the services that storage could provide. Regulation should have a vision, and could play a role to accompany the future evolution of business models, regarding a number of aspects:

The business of aggregators

Many of the sources of energy storage are very small (such as devices directly connected to end-consumers or electric vehicles) and it would seem impractical (or, indeed, impossible) to include them in a centralized scheme of system services. Aggregators could help to overcome this problem. Their business relates to grouping smaller-scale producers and consumers to reach the minimum size required for trading energy or offering services at wholesale level. They could become an important intermediary allowing a centralized management and operation of distributed means of flexibility, including demand response, electric vehicles and storage.

As this is an emerging actor in the power sector, market access is not yet fully established in many countries. Some balancing markets are not open to aggregators, impeding them to extract the maximum value from their flexible assets. Regulators, thus, should promote the process of introducing aggregators in balancing markets, by boosting the communication and collaboration between TSOs and aggregators to clear any technical barriers. Besides granting market access, some special rules might be necessary to account for limits in terms of energy capacity. The limit of energy capacity is common for many short-term flexibility means such as demand response and storage, which could supply the required up- or downward adjustment only for a limited duration, though with very short response time. The relaxation of balancing market rules has been discussed above. It could also be anticipated that the procurement of ancillary services is gradually opened to aggregators, once their technical eligibility is proven. Performance-based procurement of ancillary services, as discussed above, probably would encourage aggregators further to enter this business.

The business of renewable generators

The massive integration of RES-based generation will increase significantly the variability and intermittency of supply. This could be managed in a centralized manner by TSOs, and/or in a decentralized manner by setting incentives for (at least partially) firming renewable output. Such regulatory incentives could be set up to trigger the realization of combined power plants, virtually linking a number of renewable generators and means of flexibility[23], or to include energy storage directly into the renewable producers' business case. Numerous analyses investigate the benefits of hybrid RES/storage systems including battery-, hydrogen-, or flywheel systems (e.g. Dufo-Lopez et al., 2009; Nirmal-Kumar and Garimella, 2010; Diaf et al., 2010; Nair and Garimella, 2010) or the optimization of such integrated projects for the specific case of isolated island systems (e.g.

23 A virtual power plant (VPP) is a "multi-fuel, multi-location and multi-ownership power station, which generates electricity in many locations in the grid" (EC, 2001). An adequate proportion of secure and fluctuating generation plants will allow to compensate deviations from predicted power output due to fluctuating sources by power reserves coming from demand side management and storage. In this way, the VPP is able to offer balancing services like a traditional power plant. In Germany, for instance, Evonik Industries and steag Saar Energie operate a VPP that participates in the balancing market with a balancing power of about 1 GW, providing primary control power and minute reserve.

Diaf et al., 2008; Sreeraj et al., 2010; Carapellucci and Giordano, 2012; Prodromidis and Coutelieris, 2012).

Today, feed-in tariffs are time-independent. New mechanisms could foresee support payments differing between peak and off-peak periods (as for instance practiced in California, where the remuneration of biogas generation differs between summer and winter as well as between peak-, shoulder-, and off-peak periods) or for instance a special premium for renewable generators that provide firm power when needed.[24] The last could be provided (a) for any RES power facility eligible to FIT that could offer dispatchable power and meet base-load power demands or (b) during peak periods. Alternatively, regulators could oblige new installations of intermittent RES to include a certain amount of storage into their project, as is currently implemented in California (CPUC, 2010). It is important to note, though, that these are possible policy approaches, but that it is beyond the scope of this report to advocate any particular position. This would require a careful assessment of which policies would be optimal from an economic and societal perspective, taking into consideration also the impact of heterogeneous national approaches on competition.[25]

The business of "prosumers"

Another driver, coming from the demand side, refers to the trend towards smarter grids, distributed generation and active demand response. It could be anticipated that another type of actor – who can be described as "prosumer", i.e. producer or consumer depending on time – could substantially gain in importance. This would mirror in more two-way flows to be managed at distribution level as well as an increase in local congestion, and also would pose additional challenges related to further coordination between transmission and distribution network development.

A recent change in German legislation does address this issue. Accordingly, the Erneuerbare-Energien-Gesetz now makes it for owners of decentralized solar PV facilities more attractive to self-consume generated electricity. Consider for instance the case of a small PV system (< 30 kW); in addition to the regular feed-in tariff (24.43 ct/kWh), there is a payment for domestic use of own production of 8.05 ct/kWh (if less than 30%) or 12.43 ct/kWh (if more than 30%). Adding up the saved cost of purchasing this electricity (~22.5 ct/kWh) results in net gains of about 6 ct/kWh (<30%) or 10.5 ct/kWh (>30%), respectively, when the electricity is consumed domestically. This provides, first, incentives to shift demand to those hours where the PV device is producing; and, second, there are incentives to invest in storage devices (especially thermal storage systems).

But again, the losses in storage as well as the premium payment design (level, as well as the inclusion of time component) are essential for the viability of the storage business case for prosumers (Nekrassov et al., 2011) and the impact on the grid. It is not straightforward that an incentive scheme favoring self-consumption will reduce the pressure on distribution grids. For instance, the incentives as formulated in German law presented above are provided in terms of energy, not power. Annual peak power injection

24 Such need could be assessed by estimating the avoided grid investment and dispatch costs.

25 It also needs to be considered that in the future power system, market players will be exposed to new framework conditions. A renewable generator being eligible to a feed-in-tariff scheme today, will be in a completely different situation in 2030, with expired public support for the electricity generated but also amortized assets that can still be used to participate in energy markets. Individual cost-benefit considerations may reveal a positive business case for electricity storage in certain cases here.

as well as peak load may not necessarily decrease if a storage device is used. For instance, injection peaks may not be avoided if the storage is already fully charged on an exceptionally sunny day, or peak load may not decrease when the storage is already empty on a day of exceptionally high load. Average load will decrease but peaks may not. Hence, the introduction and design of this kind of premium payment certainly needs special regulatory provisions. This could alleviate the pressure of grid expansion, but will certainly exacerbate the heterogeneity in national renewable support policies further.

Moreover, a premium payment to 'prosumers' might result in a sub-optimal outcome in the absence of network constraints. One can imagine a situation with abundant grid capacities available, together with the feasibility to include a larger-scale, centralized storage unit into the system. Subsidies to distributed generators favoring self-consumption and incentivizing the installation of local storage devices might hamper to benefit from the scale economies that could be realized and it probably will be inefficient to connect a storage unit at every RES generator. Hence, such support mechanisms should be considered and designed carefully taking into consideration a system perspective.

Ownership of storage assets / priority of storage usage

A lively debate regarding the ownership of storage assets is on-going, in Europe but also elsewhere. A recent change in Italian legislation (Legislative Decree 28/11 implementing Directive 2009/28/EC) calls on the TSO to identify in its network development plan, the reinforcements necessary to ensure that renewable generation is fully dispatched (avoiding curtailments), stating that these interventions may include storage systems. A subsequent piece of legislation (L.D. 93/11) did not clarify the issue. On the one hand, it confirms the prohibition for the TSO to produce or supply electricity and to control generating plants; on the other hand, it affirms that following L.D.28/11, (i) the TSO can build and manage 'diffused' storage systems such as batteries; and (ii) the construction and operation of PHS plants included in the network development plan should be contracted through auctions.[26]

The ownership discussion touches three areas of concern. The first regards possible anti-competitive effects (*How do ownership patterns impact on competition?*). Given the principle of unbundling, the eventual impact of regulated ownership on competition needs to be carefully examined before granting it. One should be aware that part of the deregulated actors' revenue may come from the provision of ancillary services what explains the vigilance of the market players over the ownership debate. One plausible mechanism lies in the notion of "residual capacities" after commercial trading. Looking at the possible horizons of deciding the usage of storage (forward, day-ahead, intraday and balancing market, real-time balancing), one could see that the use of storage by TSOs actually comes at the last place. It has been shown that the residual capacities of storage, once put at the disposal of a TSO, could effectively contribute

26 In the US, a similar debate is ongoing. Several battery storage providers have applied to be considered a transmission asset, with cost recovery via grid charges. FERC gave its approval in some cases (e.g. an NaS battery proposed by Electric Transmission Texas, Presidio, completed in 2010) whereas for other projects FERC made the decision conditional on the respective ISO approving the project as part of its transmission planning process. CAISO did take a negative decision arguing that unlike capacitors and other substation equipment, storage units could participate in competitive markets, and thus, a guaranteed cost recovery would place independent projects with similar characteristics at a competitive disadvantage (EPRI, 2010).

Box 5: Interesting pilot projects on 'prosumer management'

The Isernia Project (Molise Region, Italy), initiated in 2011, tests an innovative model for the automation and management of distributed generation involving so called 'prosumers'. Monitoring is managed through a broadband connection. Nearly 8,000 'smart info devices' for customers connected to the low-voltage grid have been installed to provide information about energy price changes based on time slots. Besides, also the installation of a charging station to power a fleet of five electric vehicles, integrated with a solar PV plant and an electricity storage system are part of the project. The storage may also be used to support system stability on medium-voltage lines, or for peak shavings and load profiling, and can replace the charging system or receive energy directly from the PV plant.

Western Power Distribution (UK) initiated a demonstration project (BRISTOL) investigating the potential for battery storage in combination with solar PV generation installed on private homes, schools and an office building to provide network and customer benefits. The battery will be „shared" with the DNO, using it for network management, and the customer. A variable tariff will incentivize the customers to use the battery to reduce electricity consumption at peak times. The project received a £2.2mn grant from the Low Carbon Networks Fund.

The Sol-Ion Project, a French-German partnership bringing together research institutes, power industry and battery manufacturers (E.ON, Fraunhofer, INES, ISEA, ZSW, Saft, Tenesol, and Voltwerk) develops an integrated solution for the conversion, storage and management of distributed generation. Li-ion batteries are connected to solar PV systems and two large field demonstrations, one in France and Germany each, are currently realized. The objective is to shift excess power production at noon and to make it available for use in evening periods. Self-consumption shall be maximized at the same time that backup power is provided and the grid injection of any power remaining is managed.

to balancing (He et al., 2010). A regulatory decision to ensure that the residual capacities of any asset, including storage, would not be wasted if they could be used for ancillary services, and would be fairly remunerated, is required.

The second concern regards the viability of business models (*Which ownership pattern is a precondition for implementing a certain business model?*). The regulated-driven business model does not necessarily require ownership by a regulated actor. System operators could always contract the ancillary services with third parties. The necessity and benefits of the regulated ownership might be justified in case that the only (or most of the) deployable services of a storage unit fall into the category of the regulated services. This could refer to the niche applications of some small storage units featuring high power- and low energy capacity, thus, ensuring technically that their use is highly beneficial for system stability but will not introduce interference to competitive activities.

The third issue regards the efficiency of the business model (*Which ownership pattern is more efficient in realizing a certain business model?*). The choice of the procurement and remuneration forms of ancillary services should be analyzed in a broader framework taking into account the specificity of the underlined service, the scope of beneficiaries and transactions costs. One important difficulty, often relevant for assets whose benefits could overlap with the regulated assets, is the asymmetry of information. For instance, the resistance of a commercial investment in storage near to a congested line might be explained by the uncertainty regarding a potential increase of grid capacity in the future. However, this barrier is not insurmountable. The case study of the SSE storage park shows that the regulated system operator could communicate its grid development plan upon a sufficiently long time horizon to reflect the requirement of the services and mitigate uncertainties for investors. Regulators could play an important role in fostering the communication and mutual planning between the regulated and deregulated actors.

Grid tariffs

Grid tariffs applied to electricity storage, which is typically treated as every other generator or load, are widely heterogeneous across Member States (ENTSO-E, 2011). The major part (if not all) of the network tariff is levied on the L-component. Thus, in many countries, electricity storage needs to pay the full network tariff during charging, and in the UK for instance, storage operators have to pay also the Balancing Services Use of System Charges even though their assets may contribute to balancing the system. In a few other countries, ad-hoc tariffs are applied to storage (see also Nekrassov et al., 2011). In Switzerland, the grid tariff to be paid is based on the ratio between the feed-in/feed-out energy. In Germany, the recently implemented changes in legislation exempt new electricity storage facilities from grid tariffs for a period of 20 years and expansions of PHS units for 10 years.

Whether or not individual national initiatives implemented to support the deployment of energy storage are appropriate needs to be discussed based on economic fundamentals. But generally, charging the L-component of the grid tariff on storage is not well founded for two reasons. First, a storage unit is not the end-user of electricity (it "consumes" to store for later re-production). Second, storage operators are very elastic to price signals, more elastic than any other type of generator or consumer. More importantly, the grid tariff should be based on the principle of cost causality. If an electricity storage unit is systematically using the grid during off-peak periods (a behavior being in line with the arbitrage business model for the charging mode), it should not be considered triggering grid investment. Furthermore, it may reduce losses of the cable by leveling the line loading. The introduction of a time component in grid tariffs would allow for a more efficient use of the grid asset, and would certainly take into account the impact of storage units on grid investment needs.

Furthermore, as Europe intends to move towards one internal market, here is the risk that heterogeneity in national approaches leads to distortions in competition. Ruester et al. (2012) discuss the need for a general harmonization of transmission grid tarification. A study prepared by Frontier (2011) shows that an Austrian PHS facility would have a comparative disadvantage of 15% of its project value compared to a German facility due to the different treatment regarding grid charges. Hence, to avoid artificial locational advantages which might result in sub-optimal investments from a European perspective, a harmonization of approaches regarding the eligibility to grid tariffs on a regional level (i.e. the Alpine region) shall be considered. Together with the removal of barriers to cross-border short-term trade, including balancing markets, this will support a level-playing field for bulk storage operators.

4.3 Need for EU involvement?

Current EU involvement in market design and regulation related to the facilitation of electricity storage deployment is limited and mainly addresses the definition of underlying principles for system operation, dispatching and balancing, and the provision of ancillary services.[27] The principle of unbundling holds

27 Directive 2009/72/EC (Art. 15) calls for transparent and non-discriminatory nature of dispatching and balancing. The same Directive includes further rules concerning the provision of ancillary services: **TSOs** are responsible for ensuring a secure, reliable and efficient electricity system and, in that context, for ensuring the availability of all

(D2009/72/EC, Art. 9, 14, 26) and there are some general rules on grid tariff design, including the definition of maximum levels for charges to be paid by generators (R838/2010, Annex Part B). The need for future EU involvement relates mainly to ensuring well-functioning markets and efficient regulation, i.e. to help to remove barriers for the participation of electricity storage in energy markets and to avoid that individual Member State initiatives impose possible distortions in competition.

First, the removal of barriers for cross-border balancing markets should be pushed, since the implementation of cross-border balancing markets is imperative to enable a better utilization of the cheapest resources and should also decrease concentration levels in national balancing markets. For instance, France and the UK have already exchanged balancing services for years. This practice could be further standardized and promoted among other neighboring countries. System imbalance netting would take advantage of opposite imbalances in neighboring control areas and thus reduce the amount of real-time energy activated (Vandezande, 2011).

Balancing market integration will also be subject to a Framework Guideline due to be developed by ACER based on Art. 6(2) and 8(6j) of R714/2009. The proposals made in the first draft published recently (April 2012) would already remove certain barriers to the deployment of electricity storage as discussed above. ACER suggests an integrated balancing market approach with TSOs working in close cooperation. Standard balancing energy products shall be defined in the related Network Code and pricing methods shall be harmonized, being based on marginal pricing. The participation of alternative means of flexibility shall be facilitated and load entities (whether through aggregators or not) as well as generation units from RES and intermittent resources shall be allowed to become balancing service providers.

Regarding the creation of capacity mechanisms there are serious concerns of jeopardizing the price signal in the energy market and of distortions in competition. It is difficult to find a one-size-fits-all design for all Member States – but heterogeneity in capacity mechanism design and remuneration schemes could distort competition among Member States. Mechanisms that could help to assure the consistency between the national energy policy and the supranational internal market establishment need to be sought. Regarding the procurement of ancillary services, ACER should take the responsibility for benchmarking national practices and formulate an opinion on the appropriateness of various methodologies employed. Good practice guidelines could be established, encouraging the use of competitive tendering instead of bilateral contracts wherever possible, and to use performance-based procurement methods in the conception of tendering to support a level-playing field for all alternative means of flexibility, including electricity storage.

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necessary ancillary services (Art. 12). The transparent and non-discriminatory nature of dispatching and balancing is treated in Art. 15. **DSOs** shall procure the energy they use to cover energy losses and reserve capacity according to transparent, non-discriminatory and market-based procedures (Art. 25). And NRAs are responsible for fixing or approving at least the methodologies used to calculate terms and conditions for the provision of balancing services (Art. 37).

5. Conclusions and recommendations

This report analyzes the role of electricity storage in the future power system with a focus on how to facilitate its deployment and operation in the EU. The future electricity system will face various challenges originating from both supply and demand side. Adaptations in system architecture are required to allow for decarbonization while ensuring stability and reliability of the system. Electricity storage technologies are only one possible type of means, amongst others like flexible generation and demand side management, to provide various services (such as capacity firming, capacity accommodation, voltage and frequency control, back-up capacity, or inter-temporal arbitrage) to the system. The system's need for electricity storage stems from the need for these services. To face up with the challenges of the future power system, a comprehensive approach to assess how to enable the deployment of electricity storage (and in the broader sense also of other flexibility means), and thus, how to establish a level-playing field where alternative solutions can show their potential, needs to be developed.

The analysis is oriented along a line of questions: First, the drivers for electricity storage deployment in power systems are investigated and it is asked whether electricity storage is a special class of assets for the future power system that should be backed by some particular market design or regulation. Second, evidence is collected on which conditions might have led to a more ambitious development and use of electricity storage in selected non-European countries. Third, a systematic approach to identifying viable business models in the European power system is provided. Finally, it is discussed whether current market design and regulation allow these business models, and if not, which changes might be needed. In what follows, the main findings and recommendations are summarized.

Are alternative means of flexibility fundamentally different? Alternative means of flexibility – including a more flexible operation of generating units as well as various demand side measures – are all able to (a) react to the system requirements of up-/downward adjustment and also (b) include the opportunity to benefit from inter-temporal arbitrage. Dissimilarities come from the form of energy in the conversion and accumulation processes. Main differences relevant to the final services that alternative means of flexibility can provide to the system are expressed in quantity and degree, i.e. response time [ms-s-min]; power rating [kW-W-MW]; and energy rating [kWh-MWh]. Therefore, one flexibility means is not necessarily superior to another. The often expressed need for electricity storage to enable decarbonization is a technical and economic question; it implies to find the optimal technology mix of flexibility that provides the required services at least costs. No particular market design or regulation for electricity storage needs to be put in place, but rather current market design and regulation should be improved in order not to impede its adoption.

Does electricity storage have a special role for the future European power system? The current renewed interest in electricity storage is motivated by new challenges of the European power system one the one hand, and technical advancements and cost reductions of electricity storage on the other. Moreover, the difficulty and high cost of grid expansion certainly also lead to more attention to the storage solution. Indeed, electricity storage could fulfill a variety of functions and provide benefits to various stakeholders. But the value of storage needs to be assessed under a double uncertainty: There is uncertainty concerning the direction and timing of innovations in storage technologies themselves, but there is also uncertainty concerning the pace of change in generation, demand and grid flexibility. It means that the future role of electricity storage technologies will not only depend on own technological and cost developments, but also on how the power system evolves. It will make a difference for technology choice and scale whether we move towards 'European-wide energy superhighways' or whether we move instead towards a system of rising local energy autonomy, featured by a further increased penetration of small-scale distributed generation and widespread demand side management, with the last also triggering increases in energy efficiency, a shift of demand to off-peak periods and investments in thermal storage devices.

Which conditions have led to a more ambitious development and use of electricity storage in some countries? Reasons originate from individual market conditions, but also from specific rules in market design and regulation. US experience has shown that the emerging policy framework at the federal level does support both development and deployment of electricity storage. First, public (co-) funding coming from organized programs is explicitly targeting RD&D in the area of electricity storage, triggering numerous research activities. Second, with FERC orders 890, 719, and 755, recent changes in regulation modify tariffs and market rules such that non-generation resources can fully participate in established markets alongside traditional generation and that providers of frequency regulation receive just and reasonable remuneration, which makes the electricity storage business case more attractive. Japan, in contrast, has a particular energy industry structure being highly dependent on primary energy imports from third countries. Supply security concerns have motivated active research as part of a strong industrial policy, which reflects in the country's comparatively strong position battery development.

Which are viable business models for electricity storage in the future power system? The core of the business model for electricity storage is how the storage facility's functionalities (regarding up- and downward adjustment and accumulation) are matched with the services to be provided. Numerous studies have shown that by focusing on only one specific application, electricity storage typically cannot reach profitability in the current market context. Today's challenge is how to aggregate multiple services and to maximize multi-income streams. This report provides a systematic approach to the search of viable business models for storage. First, the location of storage is decisive to decide the main target service storage will provide. Second, business models are categorized by the nature of the main target service, distinguishing between a deregulated-driven business model (major part of income originates from activities in electricity markets), and a regulated-driven business model (major part of income originating from offering services of which the regulated actor is the only buyer). Third, it is discussed how to coordinate the provision of multiple services in these two business models, related to the ownership, the priority of usage, the allocation of capacity, contracting, etc.

Do current market design and regulation allow these business models? The viability of a business model is directly related to whether the services which electricity storage does provide to the system or individual stakeholders are adequately recognized and rewarded acknowledging their value. Major obstacles for an efficient pricing in spot and balancing markets include ad-hoc peak load arrangements implemented in some markets, the often observed inconsistence regarding price fixation mechanisms in day-ahead and balancing markets, or restrictive bidding requirements. There is also wide heterogeneity regarding the (stage of and way of) implementation of the 3rd Package and a low degree of compatibility of market designs has been achieved so far. This situation does not only create obstacles for the transition to a single European market, but it might also hamper an efficient participation of 'new' sources of flexibility in ancillary service markets.

This report does not seek for a market design that makes business models viable (i.e. *not objective-oriented*), but does investigate if the current market design allows for potential viable business model to occur (*but condition-focused*). Proposals for improvements in market rule setting based on the scrutiny of the status quo have been elaborated:

Energy-/balancing markets: The negative effects of heterogeneity in national balancing mechanisms on competition and the completion of the internal market should be recognized in the Framework Guideline on Electricity Balancing, due to be scoped by ACER this year. The proposals made in the first draft published recently (April 2012), calling for an integrated balancing market approach and the facilitation of the participation of alternative flexibility sources in balancing markets, would already remove certain barriers to the adoption of electricity storage. However, this proposal remains silent on concrete balancing market design issues. Market rules should be modified such that they relax minimum bidding requirements and rules requiring symmetric up- and downward bids in order not to impede market access for small, decentralized market players. This will allow storage and other flexibility means to valorize services they technically can provide, and thus probably also will have a positive impact on market liquidity.

Ancillary services: The co-existence of several forms of procurement and remuneration (including mandatory provision, bilateral contract, tendering, or spot markets) can be justified on economic grounds. The suitability of certain options depends on the service targeted. However, replacing bilateral contracts by competitive tendering wherever possible could help revealing and quantifying the value of alternative flexibility means, including storage. In the conception of tendering, it is also recommended to adopt performance-based, source-neutral remuneration schemes. Such measures pave the way for transnational markets for ancillary services to emerge, leading to more efficient procurement and use of ancillary services across Europe. Political borders should not restrict the flow of ancillary services. It is the market that should create its own pliable borders, acknowledging technical and economic aspects. However, heterogeneity regarding the procurement of ancillary services might hamper an efficient sharing of flexibility resources in the European power systems.

Capacity mechanism: A capacity mechanism currently is extensively debated in several European countries. However, the necessity of such a mechanism to address the risk of long-term under-investment in (peak) generation capacity remains to be proven. Instead, curing the roots of the lack of investment incentives requires to improve existing market signals, namely the quality of price signals transmitted in energy and balancing markets and for the provision of ancillary services.

A proactive regulatory intervention could be helpful in several areas to allow the emergence of new business models. This includes the promotion of market access for aggregators which would allow for the participation of small-scale electricity storage in energy-, balancing-, and ancillary service markets; obliging or incentivizing renewable generators towards output firming or direct usage of own consumption; or defining rules for electricity storage's responsibility to bear the cost of the grid without penalizing its business model. It is important to note, though, that these are possible policy approaches, but that it is beyond the scope of this report to advocate any particular position. This would require a careful assessment of which policies would be optimal from a societal perspective, taking into consideration also the impact of heterogeneous national approaches on competition.

Is there any need for a renewed EU involvement? Current EU involvement in market design and regulation related to the facilitation of electricity storage deployment is limited and mainly addresses the definition of underlying principles for system operation, dispatching and balancing, the provision of ancillary services, and tarification. The future role of the EU mainly relates to ensuring a level-playing field made of well-functioning markets and efficient regulation by establishing best practices in the areas that have been identified above. Heterogeneities in national market design and regulatory frameworks applied to storage could impose distortions in competition, and thus, should be the main focus of EU involvement. For instance, grid tariffs applied to storage or market access eligibility deserve more exhaustive survey and benchmarking. The report also calls for a harmonized balancing market. The negative effects of heterogeneity in national balancing mechanisms on competition and the completion of the internal market should be recognized in the Framework Guideline on Electricity Balancing.

Besides, electricity storage has been identified as one key technology priority in the transition of the European power system towards decarbonization in the 2020/2050 context, but the majority of possible technologies is not yet commercially available. Market failures and high risks at stake encourage private inventors and investors to focus on projects that pay off in the near-term, whereas the optimal portfolio of solutions providing flexibility has a considerably longer time horizon – certainly looking ahead to the 2050 target. Public support is needed to reduce the risks of investment in RD&D and boost the level and timing of private investment. The report confirms the importance of EU involvement in RD&D.

Financial support to RD&D already takes place, however, support pro¬grams are hardly coordinated – neither between different Member States, nor between them and the EU. The European energy technology policy instrument in place (SET-Plan, launched in 2008) does not elaborate any comprehensive strategy for electricity storage development taking into account the whole set of technologies and their possible applications. There is no clear vision on the future role of electricity storage in the European power system. A renewed European energy technology policy, going beyond the SET-Plan horizon of 2020, should include a technology roadmap for electricity storage. Coordination among Mem¬ber State and EU support policies have to be improved and public support should target a balanced portfolio of identified key technologies, including both centralized and decentralized energy storage technologies. Areas where European players already have a strong position in RD&D and/or manufacturing and which have potential for future growth should be of particular interest.

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Annex 1: Technical Annex

Overview on electricity storage technologies

In the following, we give a brief technical overview on alternative electricity storage technologies. Detailed descriptions can be found in e.g. EC (2001), APS Physics (2009), Hadjipaschalis et al. (2009), JRC (2011), Naish et al. (2008), Chen et al. (2009), or Schoenung (2011).

Pumped hydro storage (PHS)

PHS facilities, the most widely employed electricity storage technology today, use off-peak electricity to pump water from a lower elevation to a higher one where it is stored in a reservoir. During peak hours the water is released through a turbine to generate electricity. Operating powers range from MW to some GW. Discharge durations extend from some hours to some tens of hours. The typical round-trip efficiency of large plants is about 75%. The advanced pumped storage technology can allow frequent and rapid (less than 15 seconds) changes among pumping, electricity generation and spinning modes. The construction of new PHS units is restricted by the geological potential and new facilities might face problems regarding public acceptance and environmental concerns. Recent upgrades of PHS capacities mainly came from a retro-fitting of existing installations, from adding pumped storage to conventional reservoir-based facilities, or from an increase in power rating (enhancement in the power of turbines/compressors) whereas no or minor changes in energy rating (size of the reservoir) have been implemented.

A new innovative storage solution being based on the PHS concept could be '***energy islands***'. A feasibility study is recently conducted by Dutch energy companies, and KEMA, in partnership with the engineering firm Bureau Lievense and the technology illustrators Rudolph and Robert Das. In periods of excess wind energy, electricity would be used to pump sea water out of the interior 'subsurface-lake' into the surrounding sea. In periods of low wind generation, sea water would flow back into the interior lake and generate electricity. The energy island would essentially consist of a ring dike enclosing an area of approximately 10x6km. The water level in the inner lake would be between 32 and 40m below that of the surrounding North Sea. A detailed location study including economic analyses is planned.

The world's first ***underground PHS*** facility has been proposed in Germany (Harz area in Lower Saxony), where it is planned to use former mining infrastructures to build upper and lower reservoirs and install PHS equipment. A cooperation between the Energie-Forschungszentrum Niedersachsen, Harz Energie, Thuega and Volkswagen Kraftwerke GmbH is currently conducting a feasibility study (Initiative Zukunft Harz, http://www.natur-trifft-technik.de). Another form of pumped hydro storage includes ***sea PHS***, i.e. the lower reservoir is the sea. Today, there is only one pilot project in operation in Japan, but the technical potential is substantial. EDF and ADEME are developing another project in Guadeloupe.

Compressed air energy storage (CAES)

Another type of bulk energy storage is based on the CAES technology. Energy is stored by compressing air into a reservoir using a compressor powered by off-peak (i.e. low cost) electric energy. In the discharging stage, the compressed air is released, heated with a small amount of fuel, and fed into a combustion turbine. Because the combustion turbine no longer needs to use part of its output to drive an air compressor (as the air is pre-compressed), the turbine can generate almost three times as much electricity as a conventional gas turbine of the same size. Overall energy efficiency of a CAES unit is between ~40-50%. A CAES unit needs five to 15 minutes to start up. Once on line, it can ramp up at a rate of 10% every 3 seconds in discharging mode and 20% per minute in charging mode (Fergi and Apt, 2011). Operation powers of CAES facilities range from MW to some GW. The discharge duration can reach some tens of hours. Two CAES units are operating worldwide – the world's first CAES facility in Huntorf, Germany, started operation in 1978 (compressor capacity of 60MW, turbine 290MW) and a second plant in McIntosh, US, that started operation in 1991 (compressor 50MW, turbine 110MW).

Recently, the concept of ***advanced adiabatic CAES*** has been developed and is in the demonstration stage (see also Bullough, 2004). The heat released during the compression phase will be stored before the compressed air enters into the air reservoir. During the discharge phase, the compressed air and the heat are both released, avoiding the need to burn external fuel to heat the air to drive the combustion turbine. Therefore the adiabatic CAES system can achieve higher energy efficiency rates (70%) and zero CO_2 emissions.

Flywheels

Flywheel systems store energy by converting electrical energy into kinetic energy, and restore kinetic energy to electrical energy, by means of a rotating drum (the flywheel) associated with a motor/generator set. More specifically, the core element of a flywheel, a rotating mass, is connected to a shaft power by an external source of energy. In the charging mode, the flywheel is accelerated; in the discharging mode, it is slowed down. Conventional flywheel systems run at a speed of 5,000 rpm or lower, whereas high speed systems can run at a speed of up to 50,000 rpm. More current developments of this technology relates to high-speed devices. Advantages of flywheel system include high energy efficiency and fast response time. Flywheel systems also have a higher power-to-energy ratio than battery systems. However, the standby power losses are significant for this technology. A flywheel can be completely discharged after some minutes or hours. Therefore, flywheel systems need external power to maintain a certain level of charge in the standby mode. The technology is suited for short-duration, high-power discharges, over time periods up to several minutes. Established applications include critical load and uninterruptible power supply, power quality enhancement, load-leveling, spinning and standby reserves. Flywheels are often combined with batteries to cover short duration events and save batteries lifetime. Research focuses at increasing the energy density, decreasing energy losses and finding high strength composite material. Research is also targeting cost reduction and an improvement of safety and design, given the objective to deploy this technology also in residential systems.

Superconducting magnetic energy storage (SMES)

SMES relies on a cooled super-conducting coil to store energy. More specifically, electrical energy is stored in a magnetic field within the coil. This is achieved by exploiting the property that a super-conducting coil losses resistance to electric current at a temperature of -269°C. SMES are highly efficient and can allow for large storage capacity (Naish et al., 2008). Because of its high efficiency and fast response, SMES is suitable for power quality applications and can be used to provide active and reactive power, voltage support, transmission line stability and smart grid applications. Nevertheless, this technology is associated with important disadvantages, among which are large installation surfaces and very low temperature requirements. Current research activities focus on the development of larger systems with a higher energy density, more efficient cryogenic cooling systems, high magnetic fields, mechanically secure structure and super-conducting properties of the materials. SMES can also be used in conjunction with flywheel systems (so called 'Inertial Energy Storage System' (INES)).

Supercapacitors

Supercapacitors can store energy in the electric field between a pair of charged plates. They are capable of very fast ramp-up/ramp-down, and are able to go through a high number of cycles. They also have very low maintenance needs and may be suitable for frequency and voltage regulation, pulse power, factor correction, uninterruptible power supply, spinning reserves and support for renewables and smart grid systems. The technology can also be useful for mobile applications. Nevertheless, supercapacitors are still in different stages of R&D, although some devices are becoming commercially available. Research targets nano-carbon materials to increase energy and power densities, and to enhance life cycle and charge-discharge operations.

Conventional batteries

Pb-acid and Ni-Cd batteries are technologically proven storage technologies and technically more mature than advanced battery technologies introduced below. Ni-Cd batteries have a higher energy density, longer cycle life and lower maintenance requirements than Pb-acid batteries; however, the toxic materials they contain raise recycling concerns. Both types of technologies are proven solutions to a range of electrical energy storage requirements. Indeed, Pb-acid batteries have been used in electrical power systems for more than a century, and were initially used in early municipal power systems to provide electricity at night (Baker, 2008). These conventional battery technologies are commonly used to ensure power quality through greater grid reliability, frequency control, black start, uninterruptible power supply systems, spinning reserve and peak shaving. Nickel-metal hybrid batteries offer an alternative solution solving the toxicity issue related to Ni-Cd batteries. The latter have a high energy density and are free of toxic materials. Loss rates are relatively high (Chen et al., 2009; Institute for Energy and Transport, 2011).

Advanced batteries

NaS, ZEBRA and Li-based technologies are more advanced battery technologies. ***Li-based technologies*** rely on the properties of lithium, which is the most electropositive and lightest metal, and therefore benefit from a high energy density, being especially suitable for transport and mobile applications. They also might be used to support RES integration, but further tests and demonstration projects are necessary. Among Li-based storage technologies, Li-ion batteries are relatively mature compared to the Li-polymer technology. But although Li-ion batteries have a high energy density and efficiency, they still suffer from high cost. R&D targets the development of new materials and battery designs. Nevertheless, the scarcity of lithium can constitute a barrier for large deployment. Hence, research also focuses on developing batteries based on alternatives metals that could function along the same principle as Li-Ion batteries (such as Sodium-ion batteries).

In contrast to Li-based technologies, ***NaS batteries*** are larger-scale advanced energy storage systems. NaS batteries need a high operating temperature (300-350°C) to ensure the ionic conductivity. During charging and discharging processes, the heat generated by the chemical reaction is sufficient to maintain this operating temperature; however, when the battery stays idle, it needs to consume an energy equivalent of 0.6-1% of its nominal capacity per hour to maintain the high temperature (Delille, 2010). NaS batteries are suitable for short-term storage and can be used for daily applications such as load-following and peak shaving. The technology has been developed for over 30 years, and was brought to the market by NGK Insulators (Japan) in 2002 in conjunction with Tokyo Electric Power. The technology, however, has little potential to become cost-effective. With NGK, there is only one manufacturer. Prices grew during the last few years and NGK currently is working on an optimization of system engineering because safety problems in the recent past have led to a temporary interruption of production.

The ***ZEBRA battery***, also known as Sodium-Nickel-Chloride battery, is a high-temperature battery system, too. It has better safety characteristics and is able to withstand limited overcharge and discharge (Baker, 2008; Chen et al., 2009). ZEBRA batteries are also able to support a wider temperature range than NaS batteries. However, they have a lower energy density. ZEBRA batteries are produced by MES-DEA (Switzerland), and are mainly used in automotive and mobile applications. They can also be used for stationary applications to support RES integration for load-leveling. Research is ongoing.

Flow batteries

Flow batteries constitute an alternative solution for storing energy based on electrochemical processes. Compared to conventional and advanced batteries described above, the working principle of flow batteries allows for a high modularity. The electrolytes are stored separately in large storage tanks outside the electrochemical reactor. The energy rating is determined by the size of the storage tanks and the amount of electrolytes and, thus, can be dimensioned independently from the power rating of the battery, which leads to a decoupling of the power system from the energy capacity. Therefore, it is easy to scale up flow batteries to accommodate higher capacity. Flow batteries have a large number of cycles, which makes them suitable for large storage system and high energy applications. However, flow batteries are also large and heavy. Fuel batteries based on Zinc-Bromine (Zn-Br) and Vandium-redox (VRB) are in an early phase of commercialization, whereas other types of flow batteries (e.g. polysulphide bromine, cerium-zinc etc.) are still under development. Zn-Br batteries have a lower cost than VRB, but are less efficient and have a shorter lifetime. Research seeks to increase energy density, improve membrane performance, reduce costs and find new battery designs.

Power-to-gas storage

Power-to-gas storage systems rely on an energy-consuming electrolysis process to split water into oxygen and hydrogen. Subsequently, a methane-rich gas equivalent to natural gas can be produced using the H_2 obtained and CO_2 and be fed into the natural gas network. The stored gas can be fed back to gas power stations. Hence, this technology relies on a coupling of electricity and gas networks. The roundtrip efficiency is about 70% (Schimanke, 2012). Storage capacity may be higher than for conventional PHS. The main advantage of this technology is that it allows for long-term storage. Power-to-gas solutions can help to bridge shortages due to RES intermittency for up to 2 months. At its current stage, this technology is still inefficient; it may be the only adapted solution for countries that lack potential sites to further develop PHS capacities and that aim to massively integrate RES. Pilot projects are developed by Fraunhofer IWES (DE) and Hydrogenics (CA). E.ON is developing an installation that can convert wind power into H_2 at Falkenhagen (DE, exp. to be completed by 2013).

Hydrogen storage can be considered as a specific type of power-to-gas storage. An electrolyser unit converts power into H_2 and when electricity is needed, it is transformed back into electricity using fuel cells. H_2 can be stored on a large-scale basis in underground caverns, salt domes and depleted oil and gas fields. This technology has the advantage of having a large energy rating, with a high energy density and low self-discharge rate. As such, it can be suitable in connection with large wind farms, or support power grids in isolated systems. Nevertheless, the technology still is technically immature and highly cost-intensive. Furthermore, H_2 turbine plants used to convert H_2 into electricity are currently restricted below the MW-range (Auer and Keil, 2012). Research targets an increase in round-trip efficiency, fuel cell durability and lifetime, as well as an increase of the scale of the electrolyser systems.

The hydrogen obtained from an electrolysis process can be used to produce ***synthetic methanol***, which can be used to replace fossil fuels as a means of energy storage and/or ground transportation fuel. Methanol synthesis has been a commercial process for about 80 years, and current methanol production largely relies on natural gas (Danish Technological Institute, 2011). Recent developments have allowed for the conversion from CO_2 to methanol, by combining the CO_2 with H_2. This process has been developed and tested by Luigi AG, a leader in the methanol synthesis process, and in Japan. The main technological challenge lies in the efficiency of the water electrolysis. RD&D progress on H_2 production is therefore the key to commercial development of synthetic methanol based on CO_2 conversion (Olah et al., 2009). Methanol has several advantages over hydrogen. It has a higher energy density and no cryogenic containers for storage are needed. Nevertheless, methanol's energy density is lower than that of gasoline and ethanol, and it is a very toxic material. The methanol industry is quite concentrated. Most important players are Methanex (CA), SCC (US), Helm (DE), Methanol Holdings Trinidad Ltd., Saudi Basic Industries (Saudi Arabia), Mitsubishi Gas Chemical (Japan), MSK (Serbia), Iran Petrochemical Commercial, Mitsui Chemical Inc. (Japan), and Petronas (Malaysia) (Danish Technological Institute 2011).

Gravitation storage

Energy can be stored as potential gravity power. PHS is a particular case of gravitational energy storage based on a hydraulic system. The US-firm Gravity Power has extended this concept to circumvent site constraints related with PHS installations. More specifically, the system proposed relies on two water-filled shafts connected at both ends, with different sizes. Energy is stored by pumping water down the smaller shaft to raise a piston in the larger shaft. When energy is needed, the piston is allowed to sink back down the main shaft, forcing water through a generator to produce electricity. The system is relatively compact with a modular design.

Another system that relies on gravitation uses modified railway cars on a specially built track. Energy is used to pull the cars to the top of a hill, and when energy is needed, the cars are released. The motion of these cars then drives a generator. This system is developed by the US-based Advanced Rail Energy Storage, and has a roundtrip efficiency of more than 85%. A constraint of such a system is its specific topological requirements. A demonstration project is built in California.

Thermal storage (heat and cold)

One can distinguish three broad families of thermal storage: sensible heat storage (exploiting the change in a material's temperature to store and release heat); latent heat storage (storing and releasing heat through a change in a material's physical state, e.g. liquid to solid and vice versa); and thermochemical heat storage (based on a reversible chemical reaction) (Taylor et al., 2012). The thermal power rating is mainly determined by the size of heat exchangers, pimps and other auxiliary components. The volume of the storage tank determines the energy content.

Sensible heat storage is achieved by heating a bulk material, such as sodium, molten salt or pressurized water, during the accumulation phase. Water is the most commonly used medium, and hot water tanks are probably one of the best-known thermal energy storage technologies. The heat stored can be recovered to produce water vapor, and to drive a turbo-alternator system. The Thémis Station in France uses molten salt to store heat and to simplify the regulation of solar panels (Ibrahim et al., 2009). Sensible heat technology based on hot water has a power rating of 0.001 MW to 10 MW, with an efficiency of 50-90%. Storage duration can vary from days up to a year (Taylor et al. 2012). Energy density and efficiency may be low due to heat losses. Larger-scale and cost-effective thermal storage based on water can be achieved by using naturally occurring confined underground aquifers that already contain water. The use of underground aquifers is a more economical alternative to water tank storage, whose insulation is a costly part of the installation.

Advanced latent heat technologies can store a much higher amount of energy, and rely on phase change materials. During accumulation, the material will shift from solid to liquid state, and during retrieval of energy, the material shifts back to the solid state. A heat transfer fluid ensures that heat is transferred between the thermal accumulator and the exterior environment. Sodium hydroxide is considered to be a good storage fluid. This technology has a power of 50-150 KW, an efficiency of 75-90%, with storage time between hours to weeks. However, latent thermal storage is costly.

Finally, ***thermochemical storage***, also known as bond energy storage, has the advantage of having higher energy density, and no thermal energy losses in principle even for long storage periods. Indeed, the power rating lies between 0.01 MW to 1 MW, and its efficiency is 100% in principle. However, this technology is only currently being proposed for use in the future in medium and high temperature applications. The storage time is between a few hours and a day. The economics of this technology remains uncertain.

Cryogenic energy storage (CEE) is a new electricity energy storage technology, developed at the University of Leeds (UK). Off-peak or excess electricity is used to liquefy air or nitrogen, which is then stored in a cryogenic tank. When electricity is needed, ambient heat is used to boil the liquid and to obtain a pressured gas to drive a turbine for electricity generation. A higher temperature heating source to boil the cryogen can allow for a better round-trip efficiency. CEE has a capacity of 10-200 MW, with roundtrip efficiency of 40% to 90%. It is a larger-scale energy storage technology, which can offer itself as an alternative to PHS and CAES in the longer term. Nominal discharge duration lies between 1 and 12 hours. The technology can be used for utility scale back-up or peaking functions. It is in an early commercialization stage. Highview Power (UK) implements a pilot demonstration project of 500 kW using liquid air. Other major industrial gas companies, such as Air Products and Praxair, are also looking at liquid air or liquid nitrogen as energy storage media.

Summary of technical characteristics

Table 6: Technical characteristics of selected storage technologies

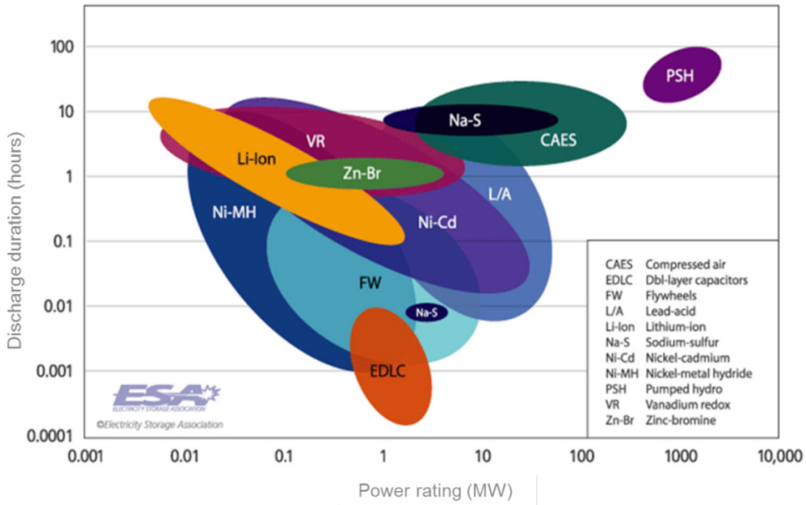
	PHS	CAES	H2	Flywheel	SMES	Super capacitors	Conventional batteries		Advanced batteries			Flow batteries	
							Pb-acid	NiCd	Li-ion	NaS	Zebra	VRB	ZnBr
Power rating [MW]	100-5000	100-300	0.001-50	0.002-20	0.01-10	0.01-1	0.001-50	0.001-40	0.001-0.1	0.5-50	0.001-1	0.03-7	0.05-2
Energy rating	1-24h+	1-24h+	s-24h+	15s-15min	ms-5min	ms-1h	s-3h	s-h	min-h	s-h	min-h	s-10h	s-10h
Response time	s-min	5-15min	Min	S	ms	ms						Ms	ms
Energy density [Wh/kg]	0.5-1.5	30-60	800-104	5-130	0.5-5	0.1-15	30-50	40-60	75-250	150-240	125	75	60-80
Power density [W/kg]			500+	400-1600	500-2000	0.1-10	75-300	150-300	150-315	90-230	130-160		50-150
Operating temperature				-20 to +40		-40 to +80				300-350	300	0-40	
Self-discharge [%/d]	~0	~0	0.5-2	20-100	10-15	2-40	0.1-0-3	0.2-0.6	0.1-0.3	20	15	0-10	1
Roundtrip efficiency [%]	75-85	42-54	20-50	85-95	95	85-98	60-95	60-91	85-100	85-90	90	85	70-75
Lifetime [a]	50-100	25-40	5-15	20+	20	20+	3-15	15-20	5-15	10-15	10-14	5-20	5-10
Cycles	20000-50000	5000-20000	1000+	105-107	10000	104-108	100-1000	1000-3000	1000-10000+	2000-4500	2500+	10000+	2000+
Power cost [€/kW]	500-3600	400-1150	550-1600	100-300	100-400	100-400	200-650	350-1000	700-3000	700-2000	100-200	2500	500-1800
Energy cost [€/kWh]	60-150	10-120	1-15	1000-3500	700-7000	300-4000	50-300	200-1000	200-1800	200-900	70-150	100-1000	100-700
Techn. maturity	Mature	Mature	Ongoing research	Mature	Mature, but only small systems commercial	Ongoing research	Available	Available	Available	Available, demo projects for RES integration	Commercialized with test projects for grid applications	Early phase commercialization for Zn-Br and VRB; research stage for other materials	
Deployment	Widespread	Ltd. (2 commercial facilities worldwide)	Limited			Widespread (small scale)	Widespread	Limited	Growing for small scale applications	Deployment in Japan		Limited	

Major possible applications	Load shifting Price arbitrage Up and down-ward regulation Peak power supply Seasonal fluc-tuation	Load follow-ing Time shifting Peak shaving Price arbi-trage Frequency regulation Seasonal fluctuation regulation	Seasonal storage Price arbi-trage Time shift-ing Forecast hedging Secondary and tertiary reserve Voltage support	Critical load Uninterruptible power supply Power quality enhancement Load-leveling Support for flex-ible AC transmis-sion systems Spinning and standby reserves	Power quality applications Provide active and reactive power Voltage support Transmission line stability Smart grid ap-plications	Frequency and voltage regula-tion Pulse power Factor correc-tion Uninterruptible power supply Support for flexible AC transmission systems Spinning reserves Support for renewables Support for smart grid systems	Frequency control Uninterrupt-ible power supply Spinning reserve Peak shaving Stationary and automotive applications	Frequency control Uninterrupt-ible power supply Spinning reserve Peak shaving	Stationary and automotive applications Support for RES, but further tests needed	Short-term storage Load following Peak shaving Support RES integration	Automotive and mobile applica-tions Load-leveling applications in support of PV and wind	Large scale storage Peak-shaving Back-up supply Support for RES Power quality applications Uninterrupted power supply Voltage support
Ongoing research activities	Higher energy efficiency and variable speed drove through double stage pumped turbine Underground reservoirs or for-mer opencast mines	Improved heat integration leading to high turbo-expander and less NOx emissions New storage locations (above ground, ves-sels etc.) Adiabatic CAES with higher round-trip efficiency, no gas combustion and longer lifetime	Increased round-trip efficiency, fuel cell durability and lifetime Large scale of electrolyser system Improve-ments in fuel cell technolo-gies	Improvement in energy den-sity and energy losses Low cost and high strength composite mate-rial Improvement in safety Design for deployment in residential systems	Development of larger systems with higher energy density More efficient cryogenic cool-ing systems High magnetic field Improvement in safety Low and high temperature super-conduct-ing properties	Nano-carbon materials to increase energy and power den-sities Enhance cycle life and charge-discharge operations		Low toxicity materials to replace cadmium (e.g. Nickel-metal hybrid bat-teries)	New materials and battery design Manu-facturing techniques to reduce costs Demonstra-tion of the battery in sup-port of RES Use of another metal (e.g. Sodium) to substitute for Lithium, which is scarce	Cost reductions and enhance modularity New materi-als in battery design (beta-alumina membrane, new electrolytes) Reduction of corrosion risks of container materials		Improvements in mem-brane performance Improvement in energy density New stack design Find new applications for mobile devices

Sources: JRC (2011), Naish et al. (2008), Zach et al. (2012)

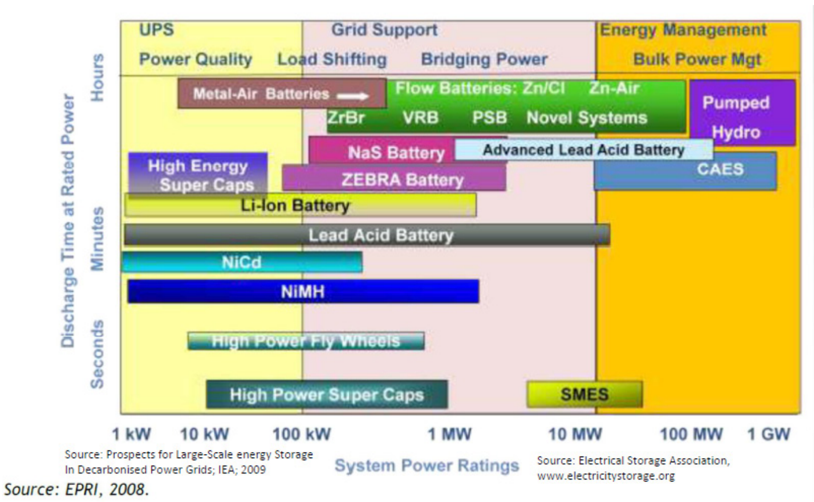
Further illustrations

Figure 10: Categorization among discharge duration and power rating



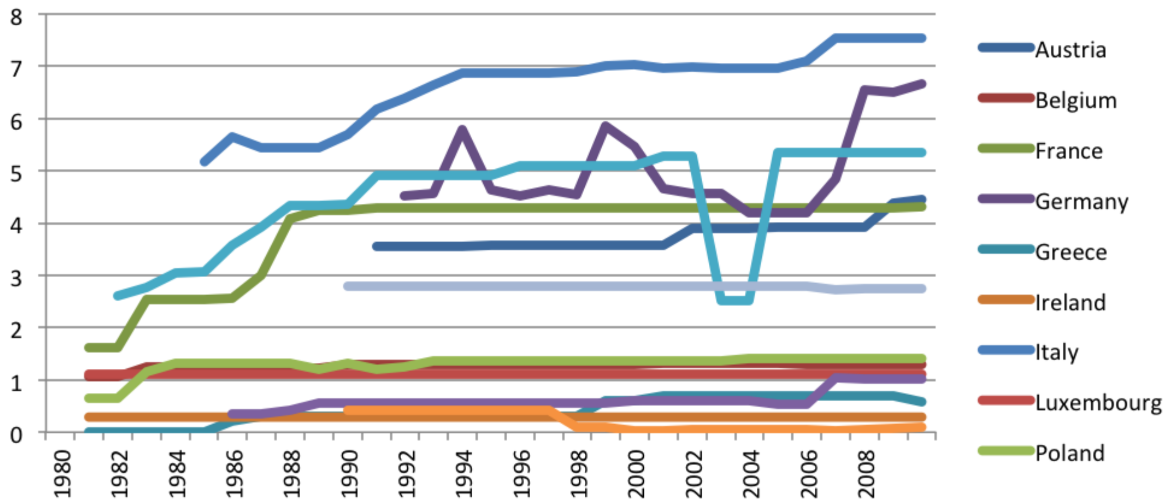
Source: Electricity Storage Association (2011)

Figure 11: Suitable applications for different storage technologies



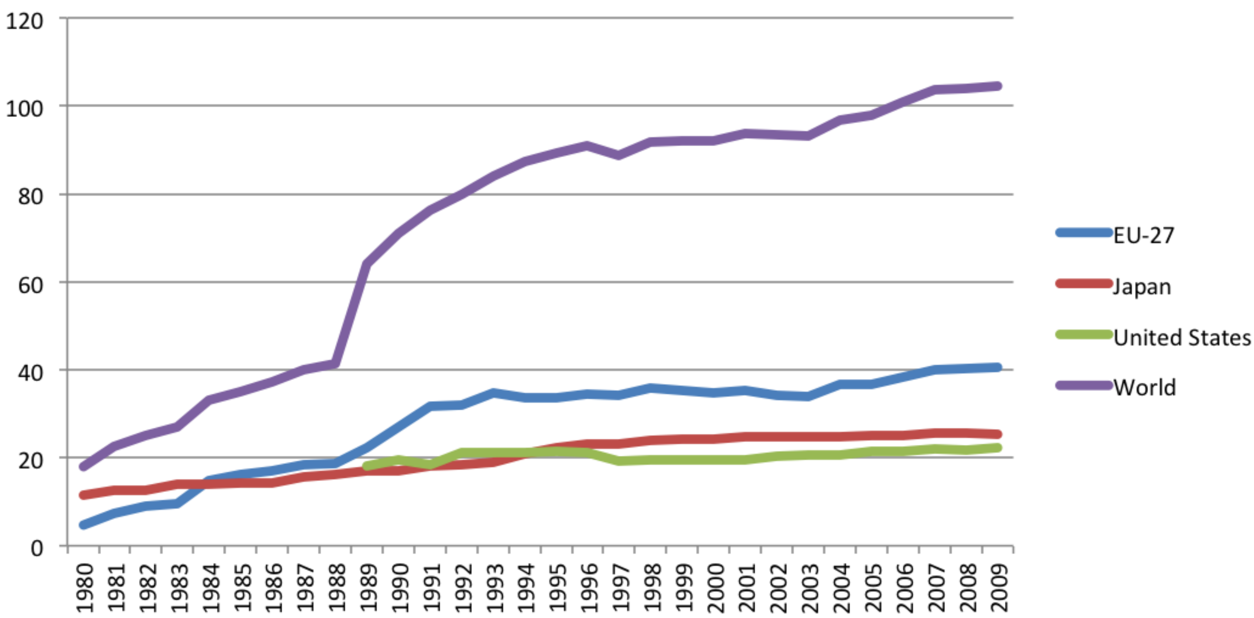
Source: Own depiction using data from US Energy Information Administration

Figure 12: Development of installed PHS capacities in selected EU countries (GW)



Source: Own depiction using data from US Energy Information Administration

Figure 13: Development of installed PHS capacities worldwide (GW)



Source: Own depiction using data from US Energy Information Administration

Costs of storage technologies

The relevant costs that should be considered are *life-cycle costs*, which do not only account for the initial investment, but also for operation and maintenance as well as residual costs at the end of the life cycle (see also Delille, 2007; Schoenung, 2011). Thereby, initial investment costs consist of the cost of the power conversion system, the cost of the storage unit and auxiliary costs such as costs related to engineering or connection with the network. O&M costs, which can be fixed or variable, include components related to the replacement of materials, re-investments, etc. Residual costs are costs related to the deconstruction of the system, recycling of materials, etc. Table 7 provides some cost data of selected storage technologies.

Table 7: Capital and O&M costs of selected technologies

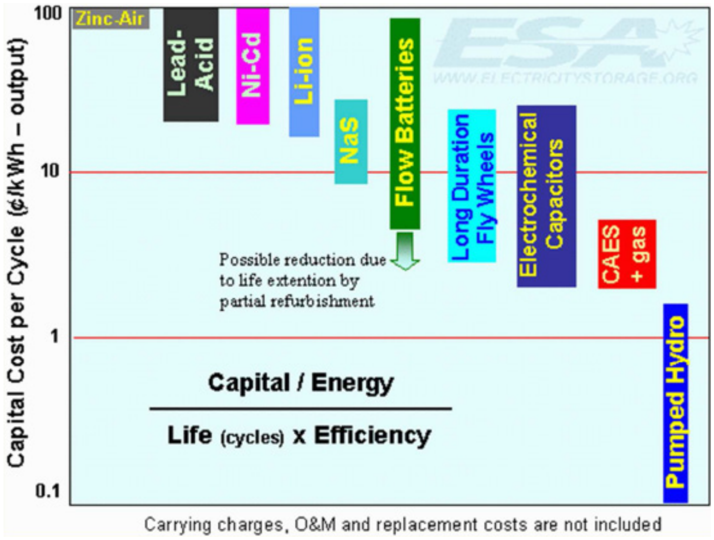
Technology	Capital costs		O&M Costs
	Power conversion (€/kW)	Storage unit (€/kWh)	Fixed O&M costs (€/kW.year)
PHS	900[a]	56 [a]	
CAES	520[a]	4[a]	
Advanced Pb-acid batteries	300[a]	250[a]	
Pb-acid batteries with carbon-enhanced electrodes	300[a]	250[a]	
Li-ion batteries	300[a]	450[a]	
NaS batteries	260[a]	260[a]	30-40[b]
ZEBRA batteries		400-500[b]	
ZnBr batteries	300[a]	300[a]	
VRB batteries	300[a]; 1750[b]	450[a]; 215[b]	40,000 (1MW/6h)- 230,000 (10MW/6h)[b]
Flywheels (high speed composite)	450[a]	1195[a]	
Supercapacitors	370[a]	7470[a]	

Notes: [a] *Data from Schoenung (2011). The storage cost is a discounted cost, based on an interest rate of 10%, an inflation rate of 2%, and 10 year storage system life. Power conversion and storage costs account for inefficiency of the system. A conversion rate of 0.747€ per USD (corresponding to 5 years average exchange rate 2005-2009) is used.*

[b] Data *from Delille (2007).*

[Remark: Not all cost components are known. It should be noted that evaluating life cycle costs is a delicate process, mainly because of the large diversity of solutions within each broad group of technology and substantial uncertainty regarding the lifetime of these technologies. Hence, the above cost data should be taken with care; these figures are intended to give a general idea rather than the exact costs. Moreover, there is a related issue on various hypotheses (technical and economic) based on which these cost data have been computed.]

Figure 14: One-time cost of storing 1 kWh



Source: Belmans (2011)

Scenarios for the penetration of electric vehicles

Kampman et al. (2011) present three scenarios for the penetration of electric vehicles:[28]

- **Scenario 1**: A 'most realistic' scenario: about 3.3 million EVs in the EU in 2020 and 50 million EVs on the EU roads in 2030. Most of these EVs are Plug-in Hybrids (about 60% of all EVs), the remainder are FEVs and EREVs. Smart charging is assumed to become standard after 2020, to avoid grid overload problems.

- **Scenario 2**: A scenario where EVs will gain some market share, but remain a relatively small part of the car fleet. This scenario leads to about 2 million EVs in 2020 throughout the EU, increasing to 20 million in 2030. PHEVs again take the largest share, about two third, in EV sales. As the sales remain limited, it is assumed that smart charging is not applied on a significant scale.

- **Scenario 3**: This scenario assumes a technological breakthrough in battery technology in the next decade. In this scenario, EVs become competitive with ICEVs. This scenario leads to 5.5 million EVs in 2020, and 93 million in 2030. Again, about two thirds of EV smart charging will be adopted from 2020 onwards, for the same reason as in Scenario 1.

Table 8: Penetration of electric vehicles in 2020 and 2030 in different scenarios

	EVs in 2020	EVs in 2030	Smart charging…
Baseline scenario	3.3mn	50mn	Assumed to become standard post-2020
Pessimistic scenario	2mn	20mn	Only applied on limited scale
Optimistic scenario	5.5mn	93mn	Assumed for majority of EVs

Source: Kampman et al. (2011)

28 **Full Electric Vehicles (FEVs)** have an electric engine and batteries for energy storage, no internal combustion engine (ICE). **Plug-in Hybrid Electric Vehicles (PHEVs)** have both an ICE and an electric engine, with a battery that can be charged on the grid. **Electric Vehicles with a Range Extender (EREVs)** have an electric engine and an ICE that can be used to charge the battery and so extend the vehicle's range. The battery of an EREV can be charged on the grid.

An interesting pilot project of the vehicle-to-grid (V2G) concept is realized on the island of Bornholm, Denmark. Project partners include Østkraft (Bornholm's power utility), the Technological University of Denmark, DTU/Risø National Laboratory, DONG, IBM, Siemens and the Danish Energy Association. The aim of the project ("EDISON", initiated in 2009) is to use V2G to facilitate the installation and operation of more wind turbines. Currently, about 1/5 of the island's electricity comes from wind, even though it has enough capacities installed to meet 40% of its needs. Curtailment is common practice. Batteries of parked electric vehicles will be used to store excess energy during periods of excess wind generation, and then feed electricity back into the grid when the weather is calm. The initial focus thereby is on small cars used in the municipality's home nursing services and administration. In a later stage, delivery vans might be included, too. The project is supported by government research funds, allocated by Energinet.dk.

Annex 2: Summary of energy market arrangements

Table 9: Survey of day-ahead spot market, balancing market and peak load arrangements in selected EU MSs

	Power ex-change	Day-ahead market		Peak load arrangement	Bidding rule and price fixation in balancing market
		Cap for bid (€/ MWh)	Floor for bid (€/ MWh)		
AT	EXAA			Secondary and tertiary power controls procured through public tenders (participation reserved for pre-qualified providers)	Pay-as-bid
BE	APX-Endex/ Belpex	3000	0.01	Secondary reserves procured through tendering (1a-contract), remunerated through cost-based capacity payment and energy delivered	Past: Pay-as-bid + average pricing Since 2012: Marginal pricing mechanism with an extra incentive component for large imbalances
DK	Nord-pool	2000	-200	Eastern Denmark relies essentially on long-term contracts and availability payments, completed by daily auctions to a lesser extent	Marginal pricing
FL	Nord-pool	2000	-200	Fingrid owns gas turbines essentially for disturbances reserves, and partly contracts	Marginal pricing
FR	EPEX	3000	-3000	Secondary reserves procured through bilateral contracts, remunerated through a fixed/pre-determined capacity payment and a fixed/pre-determined energy payment Fast and complementary reserves contracted through a yearly tendering process, during which capacity is reserved; these reserves are compensated by a fixed price for capacity (availability payment for capacity reservation, negotiated between the provider and RTE) and an energy price based on pay-as-bid	Pay-as-bid + average pricing
DE	EPEX	3000	-3000	Primary and secondary reserves must be provided for all plants with 100MW of capacity and higher; primary reserves paid for capacity, secondary reserves paid for capacity and energy delivered; secondary reserves procured through monthly auctions Minute reserves: competitive tendering Tertiary reserves: Daily auctions, remunerated based on capacity and pay-as-bid for energy delivered	Pay-as-bid + average pricing

IT	IPEX	3000	0	Terna uses an ancillary services market to ensure the availability of an appropriate amount of reserve, participation in the market mandatory Generation units able to provide secondary reserves must offer their band in the ancillary services market Tertiary reserve mandatory, remunerated on the basis of pay-as-bid	Pay-as-bid
NL	APX	3000	0.01	Regulated capacity is contracted for a full year, through a secondary reserve contract, by means of a public tendering; providers of this capacity receive a payment for capacity (specified in the contract) and energy delivered Reserve capacity: mandatory provision, remunerated based on marginal price for energy	Marginal pricing
NO	Nord-pool	2000	-200	Statnett runs an option markets, RCOM (Regulated Power Options Market) to secure sufficient resources RCOM is operated on a weekly basis	Marginal pricing
ES	OMEL	180.30	0	Secondary reserves procured through auctions (daily basis), remunerated through band (bids on the quantity to be increased or reduced in MWh and its price in €/MWh; remuneration based on the band marginal price for each hour) and energy delivered (based on the marginal price of tertiary energy regulation) Tertiary regulation is procured by means of a continuous auction, with energy remunerated at the marginal price and capacity not being remunerated (no availability payment)	Marginal pricing
UK	APX UK			Short-term operating reserves: competitively procured (3 times a year), service providers paid based on an availability payment and a utilization payment based on energy delivered	Pay-as-bid + average pricing
Sweden	Nord-pool	2000	-200	Svenska Kraftnät relies on long-term contracts	Marginal pricing

Annex 3: Conclusions Industrial Council Meeting (based on report version "V0", 02/2012)

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Professor at Department of Economics, University of Oslo

Submission date: March 15, 2012

My comments are based on the first draft of the report dated February 2012, as presented at the meeting of the Scientific Council in Brussels on February 29, 2012.

Overall assessment

Overall, the analysis is well structured and the main issues are covered. The main problem with the report as it now stands it that it is not clear what the underlying problem (market failure) is and hence why regulation is needed, specifically regulation at the EU level. Also, it would seem that the underlying issue is flexibility rather than storage – or, put differently, that storage is a potential answer to the question of flexibility – but this is not brought out sufficiently clearly.

Other comments

What is the economics of electricity storage? Presumably tradeoff between fixed costs of investment (either in the facility itself or in devices to manage it) on the one hand and price (value) differences between different time periods and (expected) value of lost load (black/brown out) on the other.

What is the market failure? For technologies suitable for peak-shaving etc. presumably prices in short-term markets could be sufficient to provide the correct signals (assuming agents are indeed exposed to such prices and they are correctly set). For frequency control, voltage support etc. decentralized operation is not practical and hence price signals will be determined by the contracts with system operator.

This implies that one main problem is ensuring that short-term price variation (in balancing, spot and other short-term markets, including grid tariffs) reflects the underlying value of electricity and hence give the correct signals for decentrally-operated storage facilities. This might require (or lead to) physical investment (meters, intelligent operational devices) and new contractual arrangements (say, between distributors and load entities).

The other main problem seems to be with developing contractual arrangements between system operators and relevant sources of system services, taking account of transaction costs (many small sources will be costly to contract). In particular, there is the problem of obtaining a portfolio of sources of system services, including flexible generation, demand management and storage.

Transaction costs would seem to be an important issue. Many of the sources of storage are very small (such as domestic heat and electric cars) and it would seem impractical (or, indeed, impossible) to include these in a centralized scheme of system services (frequency control, voltage support etc.); such small sources have to be operated in a decentralized manner.

This raises the question of the role of storage relative to other forms of flexibility, including flexible generation and demand management. One could ask whether storage is getting too much attention, especially relative to demand management, as a source of flexibility to meet the needs created by the introduction of intermittent renewable electricity generation.

In fact, much of what is thought of as storage (such as water boilers and electric cars) is really a question of demand management.

In other words, it is not clear that the underlying drivers, including new demand for flexibility generated by the introduction of (intermittent) renewable energy and new technologies for storage, represent a qualitatively new problem that requires fundamentally new regulation; rather, it would seem that the drivers enhance the need for developing efficient price structures (energy markets and grid tariffs) and efficient sourcing of system services.

The arguments for EU involvement would hence seem to be related to the more general issues of ensuring well-functioning markets and efficient regulation. In addition, there may be a rationale for supporting research and development on new technologies, as well as new regulations and their implementation.

In addition:

- The distinction between energy and electricity storage is blurred. Maybe one should hold on to the energy definition, in order to make clear that electricity storage is just one form of storage relevant for the underlying problem.

- While reference is made to generation and load management early on, their role relative to electricity storage sort of disappears as the analysis proceeds.

- It is not clear why electric storage and other sorts of flexibility are complements rather than substitutes; doesn't that depend on which technologies we are talking about.

- Talking about capacities, shouldn't (conventional) hydro reservoirs be included; after all, the main sources of energy storage on the generation side are hydro reservoirs, not pumped storage facilities.

- Too much emphasis on new technologies? After all, many sources of storage are already available (such as water boilers), although they require more efficient management (real-time metering, contractual arrangements).

- Not clear why current regulation/practices is insufficient to provide correct price signals.

- It does not become clear what the underlying rational for the two "viable business models" are. The right business models should be derived from the handling of the underlying problem to which storage can provide the solution (see above).

Dörte Fouquet

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Submission date: May 31, 2012

General comments

This is already a very good report, on a very interesting topic. Until quite recently storage was a bit "neglected" it seemed, however, its role in our future electricity system is most important, so this THINK contribution is very welcome. It seems that in Europe in particular the Transmission System Operators are interested in storage, at least from experience in other projects such as the StoRE project (http://www.store-project.eu/). Thus, the fact that the report also deals with other possible business models in its case studies and presents a comprehensive picture of the circumstances under which storage is or can be a business case is very commendable. In this regard, however, one could pay a bit more attention to smaller storage facilities and their specificities.

Conceptual comments

The conceptual set-up of the report is very practical and very accessible, as it always starts with the needs, then looks to experience and only as a last step asks whether and if so how the EU could facilitate deployment and operation of storage plants. From the assessments presented, it seems reasonable to conclude that such EU involvement would be adequate mainly in supporting RD&D and in creating guidelines for market design and regulation to create a framework within which storage business cases can work. Overall, the conclusions are well founded in the assessment and presented in a concise manner.

There are some minor editorial issues with the report, e.g. there is a lack of consistency in using words like "Distribution System Operator" (DSO) or "Distribution Network Operator" (DNO) which however will certainly be solved until the final report. Further, in the case studies one could make it a bit clearer who the owner of the storage plants is and in what capacity it is owned. Possibly one could have one or two more, to also reflect different sizes of storage facilities.

Comments on content

Overall, the content is excellent. Few additions could be made, for example when discussing public support one could compare the 30 million EUR going to storage under FP7 with what is going to other technologies, and the Horizon 2020 budget for storage, or one could throw in numbers from national public support. One could strengthen the report by adding some more discussion on smaller and decentralized storage facilities, possibly with more examples on how they work or would work. One could also briefly mention e-mobility in this context, even though a detailed discussion may go beyond the scope of the report.

Serge Galant
Technofi
Submission date: April 19, 2012

Introduction

This present annex aims at shedding light on the first round of discussions about the first draft report on "electricity storage". The discussion converged on a first conclusion: electricity storage allows addressing electricity flexibility as a whole, since storage is a breakthrough solution which drastically changes the stakeholder habits which have been focused so far on either hydro solutions or flexibility induced for instance by DSM.

The question and the proposed answer should read "Electricity storage: How to facilitate its deployment and operation in the EU?" Facilitating storage requires smartly combining technology excellence, regulation and market design which values the flexibility that it brings to the single EU electricity market at the right level, since in competition against other flexibility solutions.

Completeness: What is still fuzzy in the first draft report? Several issues need to be defined in the next version of the report:

- What is the legal definition of energy storage (electricity as a specific case) and its link with a flexibility market in Europe?

- What is the size of the problem when considered as part of a flexibility market and the time horizon by which market size will start matter?

- What is the cost of new storage (using worst case and bad case scenarios for electricity markets) and therefore what are the resulting storage capacities needed for Europe?

- What type of asymmetry generators and network operators face when considering storage?

- What is the influence of the number of storage operators upon the electricity market efficiency (increasing competition, cementing cartels or monopoles)?

- The example from France (hot water boiler system to store electricity at night when consumption is low) should be analyzed to show the lessons learnt on massively distributed, non-electricity storage solutions.

- Last, the figures for energy efficiencies along the whole value chain which include storage must be undisputable as well as the investment figures.

Completeness: What are the issues to be addressed in this next version?

- The full picture must address the links between electrical and thermal storage and the full picture about potential technologies must be given (liquid, air gravity, adiabatic compressed air, chemical storage…).

- The potential for cost reduction over time must be provided if possible coming from industrial validated sources; giving such figures will reinforce the credibility of the technology options.

- A section must be given on the time (flexibility) optimisation and space optimisation of storage (which has led DSOs looking into mobile storage solutions), while covering the whole value chain of the electricity system.

- For hydro storage, emphasis must be put on: (a) the new dynamic constraints put on hydro solutions when, for instance , ensuring the storage of wind electricity surplus, and (b) the need to redesign certain parts of the hydro storage value chain because of such dynamic constraints.

- The growing interdependence of the gas and electricity system makes chemical storage (hydrogen, methane…) a realistic approach: this option needs to be covered.

- The environmental impact of storage including the account for long-term hydrological changes coming from climate change and which might in turn impact the overall water balance.

- The related public acceptance of storage solutions: a major barrier comparable to the one observed for networks. The issue has even delayed demonstration projects (EDF in La Réunion).

- Recall past experience at EU level on storage development and demonstration.

Coherence: What are the potential incoherencies which must be addressed in the next version? The following issues must be addressed:

- Is storage a valuable solution for future flexibility markets in Europe? Does it bring solutions to a potential market failure (absence of a flexibility market) which in turn will give birth to other solutions for flexibility? Does it create new markets (storage operation) to address other issues?

- Is public intervention needed to create/reinforce flexibility markets? The tests of new market design; temporary subsidizing to help new markets reaching maturity?

- What would be the EU/national/regional involvement (regulations, technology development, standards…)? What type of common rules should be promoted at EU level?

- What type of interdependence storage may create between Member States since some solutions require proper geographical conditions?

- Is storage a proper solution to face the vanishing feed-in tariffs in order to inject more renewable power into the pan-European transmission network?

- What is the industrial dimension of storage for Europe (in some sectors leaders, in others followers or event absent)?

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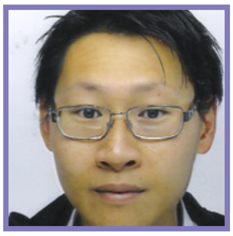

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