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Valuing dedicated storage in electricity grids

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EASAC

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Its mission reflects the view of academies that science is central to many aspects of modern life and that an appreciation of the scientific dimension is a pre-requisite to wise policy-making. This view already underpins the work of many academies at national level. With the growing importance of the European Union as an arena for policy, academies recognise that the scope of their advisory functions needs to extend beyond the national to cover also the European level. Here it is often the case that a trans-European grouping can be more effective than a body from a single country. The academies of Europe have therefore formed EASAC so that they can speak with a common voice with the goal of building science into policy at EU level.

Through EASAC, the academies work together to provide independent, expert, evidence-based advice about the scientific aspects of public policy to those who make or influence policy within the European institutions. Drawing on the memberships and networks of the academies, EASAC accesses the best of European science in carrying out its work. Its views are vigorously independent of commercial or political bias, and it is open and transparent in its processes. EASAC aims to deliver advice that is comprehensible, relevant and timely.

EASAC covers all scientific and technical disciplines, and its experts are drawn from all the countries of the European Union. It is funded by the member academies and by contracts with interested bodies. The expert members of EASAC's working groups give their time free of charge. EASAC has no commercial or business sponsors.

EASAC's activities include substantive studies of the scientific aspects of policy issues, reviews and advice about specific policy documents, workshops aimed at identifying current scientific thinking about major policy issues or at briefing policy-makers, and short, timely statements on topical subjects.

The EASAC Council has 29 individual members – highly experienced scientists nominated one each by the national science academies of EU Member States, by the Academia Europaea and by ALLEA. The national science academies of Norway and Switzerland are also represented. The Council is supported by a professional Secretariat based at the Leopoldina, the German National Academy of Sciences, in Halle (Saale) and by a Brussels Office at the Royal Academies for Science and the Arts of Belgium. The Council agrees the initiation of projects, appoints members of working groups, reviews drafts and approves reports for publication.

To find out more about EASAC, visit the website – www.easac.eu – or contact the EASAC Secretariat at secretariat@easac.eu

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Foreword

Electrical energy is notoriously difficult to store on a large scale. However, at a time when we need to decrease the greenhouse gas emissions produced by human activity, electricity is playing an increasing role in our energy consumption, and an increasing fraction of our electricity is being generated from sources that vary over time. There is therefore a strong demand for reliable information, tools and solutions that could help to equip our electricity systems with cost-efficient means of electricity storage, which is the focus of the present report.

The report has been compiled by a group of experts nominated by national science academies across Europe (members of EASAC, the European Academies' Science Advisory Council) during 2015 and 2016, when the European Commission and many of the leading stakeholders in Europe's energy sector have also been working on future climate and energy policies. Discussions between the EASAC team, the European Commission and other interested parties have been facilitated by workshops and bilateral contacts during the period of work.

The policies, directives and new technologies, which were developed and put into place in European Union Member States during the first decade of the 21st century, have encouraged rapid growth in the deployment of variable renewable energy sources, and significant progress with the implementation of energy efficiency, which together have resulted in major changes to the daily operation of Europe's electricity networks. Higher penetrations of variable renewable electricity generation and the connection of many new generators directly to low-voltage distribution grids have led to a growing need for new management tools and procedures for the electricity system, as well as updating of electricity market frameworks.

Dedicated electricity storage has historically had a relatively minor role in the management of Europe's electricity networks. However, the abilities of storage systems to contribute to the balancing of electricity supplies and demands, as well as to reserves, capacity and generation adequacy, have the potential to make storage more valuable in the future, as the penetration of variable renewable electricity generation increases further.

At the same time, there are other options that can be used for managing electricity systems, including more flexible generation, demand response, grid reinforcements, greater interconnections, and curtailment. To deliver secure supplies of affordable electricity at the lowest costs to European consumers, it must therefore be made possible for storage systems to compete with these other options, which implies changes to the current design of electricity markets.

As well as having a potential role in the toolbox of electricity system network managers, electricity storage systems are increasingly being installed by electricity consumers and households, notably together with solar photovoltaic generators. As the prices of batteries continue to fall, partly because of their increasing use in transport applications, it seems likely that larger numbers of electricity storage systems (mainly batteries) will be installed in future by electricity consumers and 'prosumers'. It will therefore become increasingly important for policy-makers and network operators to understand the potential added values and risks associated with such developments as consumers become more active players in the energy markets of the future.

EASAC welcomes the new package entitled 'Clean energy for all Europeans', which was published by the European Commission on 30 November 2016 with the aim of addressing the need for updating the designs of electricity markets in the European Union, as well as the directives for electricity, renewable energy and energy efficiency.

EASAC is pleased to offer the conclusions and advice for policy-makers, which are contained in this report, as an independent scientific contribution to inform the forthcoming debate on the November 2016 climate and energy package, which will undoubtedly involve a wide range of potential stakeholders at European Union, national, regional and local levels across Europe. In addition, the information contained in this report may be of value to climate and energy sector stakeholders in other parts of the world.

Professor Thierry Courvoisier
EASAC President

Summary

The focus of this report is on dedicated storage in electrical power systems: that is, 'electricity in – electricity out' of storage systems connected to electricity grids in the period 2017–2030. Longer-term options and non-dedicated energy storage (including heat, battery electric vehicles and power-to-gas) are also briefly discussed.

The report is intended for European Union (EU) policy-makers, investors, and other stakeholders (including system operators, generators, and electricity users) who are engaged in policy debates on the future of EU electricity grids, notably those involved in discussions on the 'Clean Energy for All Europeans' package, which was proposed by the European Commission (EC) on 30 November 2016.

The report summarises the latest independent scientific evidence on the use of dedicated electricity storage in electricity grids, explains potential impacts on electricity markets of recent and expected developments in storage technologies, and highlights what could be done through electricity market design, energy policy and investment support to ensure that grid-connected storage is used effectively in the future. EASAC did not specifically address EU research policy or industry policy in its work for this report.

Current and future deployment of dedicated electricity storage

The current (2016) deployment of dedicated electricity storage on the grid in the EU is dominated by pumped hydroelectric storage (PHS) (see Figure S1), but the deployment of lithium-ion batteries is growing fast and growth is also expected in the deployment of other energy storage technologies.

At least two EU Member States (Germany and the UK) have recently started to procure more dedicated storage for deployment on their electricity grids, and more can be expected in the period to 2030 and beyond. Against this background, two key technology developments justify the attention of EU policy-makers.

(1) As the penetration of variable renewable generation (wind and photovoltaics (PV)) increases, more storage systems may be connected to transmission and distribution grids to provide short-term flexibility in competition with other flexibility options (flexible generation, interconnections, demand response and curtailment).

(2) Small storage systems will be installed on distribution grids as consumers (mainly householders) invest in PV plus battery systems for increased self-consumption.

Market readiness of electricity storage technologies

Many different electricity storage technologies have been studied, developed and piloted over the past several decades, and research is continuing on several potentially competing options. Pumped hydroelectric storage (PHS) and possibly lithium-ion batteries appear to be ready for large-scale deployment over the next few years in grid-connected applications in the EU.

Pumped hydroelectric storage (PHS) is the most widely used and proven electricity storage technology today, with more than 48 gigawatts (GW) currently in operation in the EU28 plus Norway and +Switzerland, and approximately three times that worldwide. There is scope for increasing the output from many existing PHS plants, and several new sites could be used in the EU, so it is estimated that up to

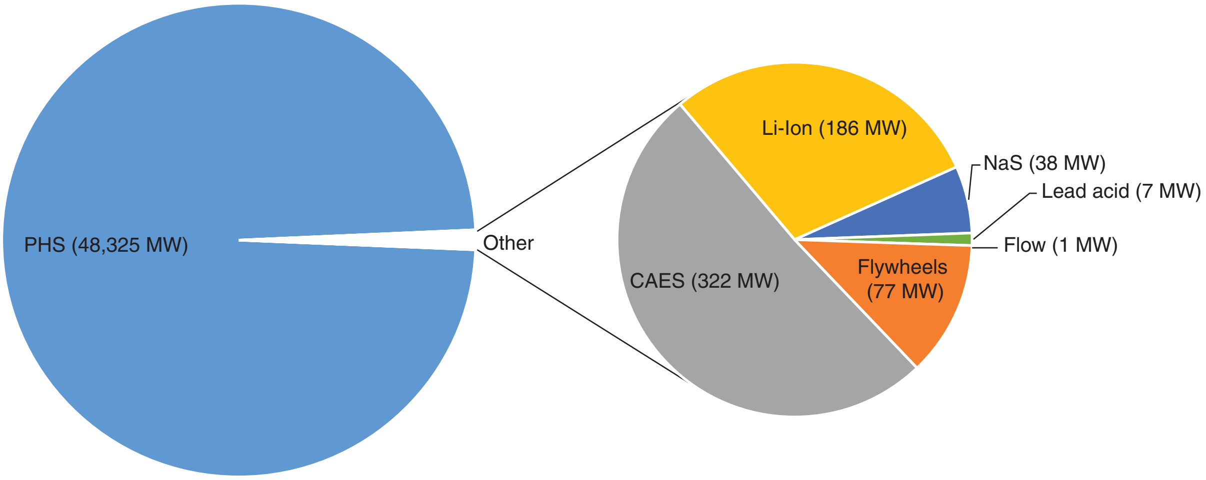

Figure S1 Operational grid-connected electricity storage capacity in the 28 Member States of the EU (EU28) plus Norway and Switzerland. Note: data were exported from the US Department of Energy (DOE) database in September 2016. Specialised applications of high-power flywheels in the UK and German fusion research laboratories and the RWE Adele Compressed Air Energy Storage (CAES) plant (which is not operational) were excluded.

about 75 GW of PHS could be working in the EU by 2030, and more could be built after that.

Battery technologies have been successfully demonstrated in both transmission and distribution grid-connected applications. Research is continuing in particular to reduce the costs and to improve the performance of batteries, and major investments are being made worldwide in new mass production plants for producing lithium-ion batteries in particular.

Future storage options research is continuing on a wide range of storage technology options, including power-to-gas-to-power, but no new storage technologies are expected to be commercially deployed on a large-scale in grid-connected applications before 2030. Similarly, the charging and discharging of electric vehicles as a (non-dedicated electricity storage) service to support the grid are being studied by researchers, but it is unlikely that such options will have a commercial role before 2030. In contrast, non-dedicated storage using power-to-heat and power to gas are less expensive and could be deployed earlier, notably as an alternative to curtailment.

Further research EASAC recognises the importance of continuing research on dedicated electricity storage technologies to reduce costs and increase performance, as well as a need for further work on the integration and modelling of electricity systems, to assess the multiple values of dedicated grid-connected electricity storage.

Policy options affecting future markets for electricity storage

Future policy options for the EU electricity sector must ensure efficient and stable power system operation with the lowest possible cost to consumers, while the fraction of variable renewable electricity continues to grow in response to a continuing drive to reduce carbon emissions. Against this background, the future deployment of dedicated electricity storage in the EU will be strongly influenced by future EU policies for the following:

(1) electricity market design (including tariff structures and the regulation of system operators);

(2) electricity system operating rules (regulations, directives and network codes);

(3) technology investments (transparent planning to build investor confidence);

(4) involvement of consumers and prosumers (including self-consumption).

Conclusions and advice for policy-makers

The conclusions and policy advice, which are presented below, have been compiled by EASAC, on the basis of the peer-reviewed information and independent analyses that are presented in this report.

What is the value of dedicated storage?

1. **The value of dedicated storage on an electricity grid is system dependent.** The roles and opportunities for electricity storage and its competitors grow as the electricity systems grow, in particular as the penetrations of variable renewable generation increase. The same storage technology can offer several different services to the grid, and have different values in different situations. The business case for investing in storage becomes more attractive when one specific storage system can viably compete in more than one role/market at the same location (multiple use with value stacking).

2. **Storage is widely acknowledged today as an expensive option, but its costs are falling and its value is improving.** There are many conflicting claims and projections for current and future costs of the different storage technologies, and many ongoing research projects aiming at cost reductions. Among the different storage technologies, it is clear that batteries have the highest cost reduction potential and their costs are falling fast, partly as a result of the economies of scale that accompany their growing use, especially in transport applications. In contrast, the costs of other storage technologies are coming down more slowly but, for future large-scale applications, PHS in particular may offer good value for money in suitable locations.

3. **Storage adds value to electricity grids by contributing to the growing demand for flexibility (including congestion management), which is resulting from increasing levels of variable renewable generation (notably wind and PV) on electricity grids.** However, the demand for flexibility will be met in future by combinations of five competing options**,** namely flexible generation, curtailment, grid reinforcement/interconnections, demand response and storage. Flexible generation has been a major source of flexibility historically, but as capacity factors for peaking plants fall, investments become less favourable (particularly in the absence of capacity markets). Where they are feasible, curtailment, grid reinforcements/interconnections and demand response are typically cheaper than dedicated storage, but (a) the scope for *curtailment* is limited, the market is not yet ready in

many parts of the EU for power to heat, and power to gas is not yet commercially available, (b) it can take many years to build new grid reinforcements/*interconnections* because of public resistance, and (c) in many areas, systems may not yet be in place to manage dispatchable load programmes and end-use constraints may limit the potential for *demand response*. Consequently, it is reasonable to expect a growing penetration of dedicated electricity storage in future markets for flexibility on the grid.

4. **Storage adds value to electricity grids by contributing to balancing, reserves, network capacity and generation adequacy.** PHS has been used for many years to provide balancing, and other storage technologies could contribute similarly to balancing and, in addition, to other key components of EU electricity markets in future. The use of storage to provide peaking capacity as well as reserves, permits the most cost-effective (high merit order) generators to operate with higher utilisation levels, thereby increasing their efficiency and potentially leading to lower electricity prices for consumers.

5. **Battery storage systems are valued by consumers, who are installing them increasingly at household level together with PV systems for self-consumption (prosumers).** This growing trend, which is being driven largely by consumer preferences as well as by incentives/tariff structures, falling PV and battery prices, and technology push by suppliers can bring financial benefits to PV and storage system owners, but may add to the costs of other electricity consumers and bring new management challenges for distribution system operators. It is attracting a new source of investment capital (householders) in distributed storage systems, but is an emerging challenge from an overall system perspective.

6. **Storage is particularly valuable in isolated systems.** In islands, remote locations and micro-grids, storage is needed to balance supply and demand because isolated systems cannot benefit from the regional diversity and smoothing that takes place across large interconnected systems, such as those in continental Europe. Some of the challenges faced by small isolated systems are also faced by relatively large but isolated systems, and in areas of the EU with poor interconnections.

What are the limits of storage?

7. **Storage will not substantially reduce EU needs for back-up generating capacity** in the short to medium term. Storage has traditionally been used to smooth out peaks in demand, and it can similarly be used to smooth out peaks in supply. However, where over-capacity exists, it is difficult to justify significant additional investments in storage. As new capacity is required, storage can play a valuable role in contributing to generation adequacy and reducing system operating costs. However, none of the dedicated storage systems, which are commercially available for grid applications in 2016, is typically able to deliver its nominal power for more than about 10 hours, so they could not fill the gap when there is little or no supply from wind and solar generation during periods of several days with low wind speeds and limited sunshine. As a result, it seems likely that the most cost-effective solutions for providing generation adequacy in the coming decades will involve combinations of hydro and thermal generators along with dedicated storage.

8. **New technologies are not yet ready to deliver competitive seasonal storage of electricity for the grid.** Seasonal storage of grid electricity will not be needed until much higher levels of variable renewable generation are on line than is the case today. Nevertheless, several power to gas options are being studied with the initial aim of producing synthetic gas for transport and industry, and these could be used within a few years to avoid curtailment of variable renewable generation. In contrast, the costs of power to gas to power systems are far too high and their round-trip efficiencies too low to be deployed commercially for seasonal grid electricity storage applications within the foreseeable future, but they could perhaps be deployed within the 2050 timeframe.

What should be done to ensure that storage is used effectively?

9. **Electricity market design should deliver price signals (locational and temporal) that will encourage investments in the most cost-efficient flexibility options on both transmission and distribution grids.**

   (a) A redefinition of bidding zones (reflecting the physical constraints of the system) would help to deliver a cost-efficient mix of flexibility options and to avoid unnecessarily expensive systems being built.

   (b) Increasingly important for investors will be transparency about plans and rules for the future management of flexibility, because the marginal value of providing additional flexibility decreases as more is deployed on the grid. Particularly important for independent investors will be the planned split between (i) flexibility management within the regulated market by the network operators using interconnectors, international agreements and possibly storage and (ii) flexibility management within competitive markets by means of flexible generation, demand response and storage.

(c) Authorities in several parts of the world have put in place short-term incentives, targets or demonstration programmes to promote the deployment of storage on electricity grids. However, it is too early to assess the extent to which these will lead to the large-scale deployment of cost-effective mixes of flexibility options on a long-term basis.

10. **Electricity market design should address the emerging challenge of more PV plus battery systems being installed by householders on distribution grids.** Most existing tariff structures focus largely on energy used (costs per kilowatt hour) and therefore produce a lack of price signals or in some cases counter-productive price signals regarding network costs (costs per kilowatt). While consumer wishes for self-production should be respected, it will be important that the costs of grid infrastructure be shared fairly across all users, and that any additional costs, which result from new clusters of PV systems being added to the grid, should also be attributed transparently to those who create them. Similarly, any benefits to distribution system management, which result from the use of (aggregated) household storage systems, should be fairly shared between those who provide them. Time-varying tariff structures with more intelligent metering are expected to contribute to the management of these issues.

11. **Electricity market design should be technology neutral, which means that it should not create barriers to the deployment of potentially valuable systems and technologies (including storage).**

(a) Provision should be made to define and accommodate the specific features of all system assets and technologies for providing flexibility to the grid (including storage), so that they are not excluded or discouraged without good reasons. For example, without objective justifications, minimum bid sizes, lack of provision for aggregator involvement and double payments for use of grid infrastructure (payment when energy comes into and out of storage) currently limit the participation of storage in some markets.

(b) Independent flexibility providers, such as storage system owners or aggregators of many small storage systems, should be allowed to participate in multiple markets provided it is physically possible to provide the multiple services simultaneously. In addition, independent owners of storage systems should be allowed to use them for regulated functions when contracted by system operators, but also free to use the same systems in competitive markets at other times. This would improve the business case for providing flexibility (for example by using dedicated storage) and improve the management of regulated networks at the same time.

(c) Public support at EU level for investments in systems to provide flexibility to the grid (for example via the Connecting Europe Facility or the European Investment Bank) should continue to give equal treatment to potential investments in all options for providing flexibility, including dedicated electricity storage.

12. **Policy for science.** More research and development is warranted with a focus on the following issues.

(a) Continuing to reduce costs, for those dedicated storage technologies with significant potential for cost reductions, as well as pursuing continued technological advances for those storage systems. Key storage characteristics are application specific and those for dedicated grid-connected (stationary) applications are not necessarily well matched to those used for transportation (for example energy density and cycle life requirements can differ significantly).

(b) Studies and analysis (including modelling) of transmission and distribution systems and markets, including socio-economic monitoring of demonstrations and innovation programmes, and of prosumer markets, as the market design evolves to meet increases in the demand for flexibility and as storage costs fall and its deployment increases.

Target audience and aims of the report

The target audience for this EASAC report is EU policy-makers, investors and related stakeholders (including system operators, generators and electricity users) who are engaged in the policy debate on the future of EU electricity grids, notably those involved in discussions on the 'Clean Energy for All Europeans' package, which was proposed by the EC on 30 November 2016 (EC, 2016b).

The aims of the report are (1) to summarise the latest independent, objective, scientific evidence related to the use of dedicated electricity storage in electricity grids, (2) to explain the potential impacts on electricity markets of recent and expected developments in storage technologies, and (3) to highlight what could be done through electricity market design, energy policy and investment support to ensure that storage is used effectively in EU electricity grids.

EASAC's mandate for energy and climate is to provide independent scientific advice to EU policy-makers. The report therefore has a focus on the complex issues being faced by energy and climate policy-makers in the EU, at a time when the costs and performance of some electricity storage technologies are evolving fast, and EU electricity market design and related policies are being reviewed and potentially updated.

Scope

The focus of this report is on dedicated energy storage in electrical power systems: that is, 'electricity in – electricity out' of storage systems connected to the electricity grid. Other types of non-dedicated storage are discussed (for example heat storage, battery electric vehicles, and power to gas), but these options serve as comparators. The report focuses mainly on the period from 2016 to 2030, although reference is made to ways in which EU electricity systems and markets might evolve by 2050.

Report structure

The report begins with an introduction in Chapter 1 to the current policy discussions on electricity markets, and an overview of what has been happening recently in EU electricity markets. This is followed in Chapter 2 by a review of the commercially available electricity storage technologies and of the expected developments in the storage sector by 2030. The services offered by storage to EU markets are reviewed in Chapter 3, followed by a discussion of the modelling methods used for assessing the values of electricity storage and their main findings in Chapter 4. The policy options affecting future markets for electricity storage are discussed in Chapter 5 and, finally, the scientific evidence presented in the report is brought together in the form of conclusions and advice for EU policy-makers in Chapter 6.

1 Introduction

Many reports on electricity storage have been produced in recent years (see, for example, EC, 2011, 2016a, 2017; IEA–RETD, 2016; IRENA, 2015a, 2015b; EASE/EERA, 2013), and these reflect the perceived importance of the topic, the speed at which the costs of some storage technologies are falling (more quickly than many experts expected), the growing strength of the storage industry, the growing penetration into grids of variable renewable electricity (which has limited predictability and is not dispatchable) and the need for EU electricity market and regulatory frameworks to evolve accordingly.

This EASAC report is the result of work done during 2015/16, at the same time as the Commission was consulting and working on proposals for updating the existing EU energy directives and electricity market design. EASAC's aim was to provide an independent assessment of the potential value of electricity storage on electricity grids, on the basis of the evidence that is available in peer-reviewed scientific literature and using the knowledge, experience, expertise and analytical skills of independent experts nominated by EU national science academies. This report was finalised after the EC published its 'Clean energy for all Europeans' package at the end of 2016 (EC, 2016b), and is therefore well placed to inform the debate on the Commission's proposals, which will take place in the European Council and in the European Parliament during 2017.

At the start of the work, the following highlights were identified by EASAC as being relevant to the value of dedicated storage in electricity grids in Europe, in particular:

More variable renewable electricity generation is being connected to European grids in line with the EU energy and climate strategy, and in some cases because of national strategies such as nuclear phase-out in Germany and Switzerland. As a result, electricity from renewable energy sources is expected to increase from 26% of the total EU electricity supply in June 2015 to around 45% or more by 2030. A large part of this increase will come from variable renewable generation, notably wind and solar (EC, 2017).

Reducing greenhouse gas emissions within the EU economy is one of the priorities of the 'Energy Union' policy (EU, 2015b), which was reflected in the EU commitment to the COP21 Paris agreement in December 2015 (EC, 2016g). Emission reductions in the EU are being driven in three important sectors (power generating, energy intensive industries and civil aviation) by the Emission Trading System (EC, 2016c), and in non-Emission Trading System sectors (notably heating and transport) by the Effort Sharing Regulation 2021–2030 (EC, 2016d). Specifically, the EU's 2030 Framework for Climate and Energy set targets of a 40% cut in greenhouse gas emissions compared with 1990 levels, at least a 27% share of renewable energy in energy consumption, and at least 27% energy savings compared with the business-as-usual scenario by 2030. Electricity storage could play a role in meeting these targets by helping to balance supply and demand in ways that increase the use of clean generation and reduce the use of high greenhouse gas emission generators. (Note: storage deployment can also result in increased capacity factors in coal fired plants, thereby increasing greenhouse gas emissions (Tuohy and O'Malley, 2011).)

A growing need for flexibility in the electricity system is highlighted by the Commission in its Energy Union Communication on climate and energy (EC, 2015a, 2015b), which address demand response and storage management together as potential providers of flexibility. This Communication recognises the need to remove regulatory barriers and discriminatory rules that prevent consumers (or aggregators acting on their behalf) from using demand response and storage in an efficient manner, and from competing in electricity markets on an equal footing with wholesale market actors such as generators, traders and large consumers.

EU Renewable Energy Directive (2009) has not only encouraged the connection of a rapidly increasing amount of variable renewable electricity generation to the grid, but its Article 16.2 also introduced the challenges of *priority access* and *priority dispatch* being given to that generation even in surplus situations in the period until 2020. However, when looking at the potential for deployment and the future value of storage on the grid, it is important to recognise that priority dispatch may have to be limited at times, for example when it could put the security of the network at risk. It is also noteworthy that storage is not mentioned in this Directive.

EU Energy Efficiency Directive (2012) highlights the importance of taking storage into account in network regulations and tariffs, stating that, '*Network regulation and tariffs shall not prevent network operators or energy retailers making available system services for demand response measures, demand management and distributed generation on organised electricity markets, in particular: the storage of energy*'.

Existing generators are being replaced or upgraded. In response to the EU decarbonisation commitments, thermal generating plants (typically coal or gas fired), some of which have limited flexibility in terms of ramping rates and minimum load, are being modernised, combined heat and power plants are being retrofitted with thermal storage and new, more flexible centralised or decentralised generators will enter the market in the coming years.

The active participation of consumers/prosumers is increasing, some of whom may continue to act on their own while others may choose to play a stronger role in electricity markets via aggregators. This is because growing numbers of small PV generators are being installed by householders who are motivated to generate their own electricity. Some of these people are motivated by an interest in technology or a desire for independence, and some by a desire to reduce their electricity bills and avoid the taxes and levies that have to be paid on electricity taken from the grid. Some people are also installing battery storage systems, so that they can use their own electricity also when PV generation is low (approximately 40% of the newly installed PV systems in Germany with feed-in tariffs in 2015 included a storage unit).

EU electricity market design (legislation and regulation) is continuing to evolve under the guidance of the EC, which is working together with transmission system operators through the European Network of Transmission System Operators for Electricity (ENTSO-E), regulators through the Agency for the Cooperation of Energy Regulators (ACER), and EU Member State governments to build on the initial implementation of the 3rd package (EC, 2013a), and to update the EU Electricity Directive (2009) and electricity market design. The future commercial viability of electricity storage could be strongly influenced by the results of negotiations on the new package on 'Clean energy for all Europeans', which was proposed by the Commission on 30 November 2016. This package proposes greater participation of prosumers and aggregators in EU electricity markets, and foresees a more substantial role for electricity storage in the future. For example, electricity storage could contribute in energy, capacity and ancillary services markets, and potentially offer cross-border capacity in system adequacy assessments.

Subsidies and incentives. The EU energy sector has evolved over many decades, and its markets have been guided and controlled through a complex mix of EU and national policies, codes, regulations, incentives, taxes, levies and subsidies. As a result, the main actors in these complex markets have large amounts of capital tied up in generators and in network infrastructure, for which their businesses depend to different extents on subsidies. In addition, subsidies have triggered the growth of markets for small PV generators for households in several EU Member States. As the EU electricity market design is updated, it is expected that such incentives and subsidies will be reduced, but it is not easy to predict how this will impact on the future deployment of electricity storage.

Major new investments in improved interconnection infrastructure have been proposed by the Commission in its EU energy infrastructure package (EU, 2011) through Projects of Common Interest (PCIs) which will be funded in part by the Connecting Europe Facility. The agreed list of PCIs (EC, 2016e) includes several large-scale electricity storage projects, including pumped hydro in seven Member States, and approximately 2 gigawatt hours (GWh) of compressed air storage in Northern Ireland. A project for 250 megawatts (MW) of battery storage systems in Italy was on the list in 2013 (EC, 2013b), but later removed. The Commission's public consultation on the PCI list demonstrated clear resistance by some stakeholders to the inclusion of storage projects on the grounds that these should only be developed by deregulated companies because storage is a market activity (EC, 2016f). Stronger interconnections and grid reinforcements are expected to reduce congestion, increase electricity market competition, increase cross-border trading in electricity services and allow for balancing over larger areas, which may in turn reduce the need for storage. Stronger interconnections are also expected to permit the EU to take advantage of the regional diversity of its renewable resources. However, interconnections may take a long time to implement in some regions because of local resistance to the construction of new infrastructure (ACER, 2015).

Distribution networks will become more controllable and actively managed (smarter). The shares of generation on distribution networks are growing, as well as the use of storage for system management. Increased levels of control and communication are foreseen throughout distribution networks and at interfaces with the transmission network, with bi-directional power and information flows. Cyber-security will become increasingly important as communication-enabled components in electricity systems, including dedicated electricity storage systems, become more widespread.

Growing competition for investment funding can be expected between investments in transmission grids and investments in (smarter) distribution grids to carry more distributed generation, including small renewable generators (notably PV).

Security of supply. Among the drivers of change in EU electricity markets, the EU strategy for security of supply currently (EC COM(2014) 330) has a high priority, partly because of the volatility of oil and gas prices and partly because more than 50% of EU gas supplies are imported (15% of EU electricity in 2014 was produced using gas (Eurostat, 2016b)). Some stakeholders have suggested that electricity storage could help to improve the security of EU energy supplies, either directly by providing supplies in times of need or indirectly by facilitating higher penetrations of indigenous renewable electricity generation. However, with current storage technologies, a meaningful contribution to the security of EU electricity supplies could only be provided for a few hours and, with current costs, storage would be an expensive option compared with alternatives.

A short overview of the most relevant electricity storage technologies for integration on EU grids is presented in Chapter 2, which also summarises the current status of development and deployment of these technologies. This is complemented in Chapters 3 and 4 by analyses of the services offered by electricity storage on the grid and of its different values.

Lastly, on the basis of independent analyses of experience that have been documented from around the world, the different policy options that could affect future markets for electricity storage are discussed in Chapter 5, and EASAC's conclusions and advice for policy-makers are presented in Chapter 6.

2 Electricity storage technologies

2.1 Current deployment and key features

Information on those grid-connected electricity storage systems that are installed worldwide today is publicly available in an easily accessible database which is kept up to date by the US Department of Energy (DOE, 2016a). This database has been used to compile the overview presented in Figure 2.1, where it can be seen that more than 98% of the operational grid-connected electricity storage in the EU28 plus Norway and Switzerland in September 2016 was provided by pumped hydroelectric storage (PHS) systems connected to grid networks. In addition to PHS, the capacity of electricity storage systems that are operational on European electricity grids includes 3 compressed air storage systems, 12 flywheel storage systems (excluding specialised applications for research laboratories) and a combination of 4 main types of battery.

There is a considerable technical potential for the deployment of PHS in the EU to be increased in the coming years (JRC, 2013), and new industrial activities have been announced which aim to increase the production of lithium-ion batteries both for battery electric vehicle (BEV) and for stationary applications, including grid-connected electricity storage. More details on these potential developments are presented by technology below.

The current deployment of electricity storage in the EU is summarised in Table 2.1, where it can be seen that the total operational electricity storage in EU in 2016 was approximately 49 GW (Geth *et al*., 2015; DOE, 2016a), and the shares of the different storage technologies were similar to those in global markets. While recent estimates have been made for the operational and the potential PHS energy capacities (in megawatt hours) in the EU28 plus Norway and Switzerland, this is not available on a global level because the operating durations of many of the plants have not been recorded in the DOE database, and in many cases may actually be difficult to determine, notably for those PHS plants that operate in open-loop mode.

The data in Table 2.1 from the DOE database are for systems that were operational in September 2016. However, it is noteworthy that major steps have been taken by EU governments and their network operators (notably in Germany and the UK) during 2016 to procure grid-connected battery storage systems, which are scheduled to be built in the next few years. For example, auctions have been launched during 2016 for 200 MW of battery storage in the UK and for 120 MW in Germany.

Table 2.1 contains a summary of key information on electricity storage technologies, which is important for EU policy-makers including the numbers of systems that are currently operating in the EU, their typical capacity (in megawatts) and estimates made by EASAC of their technology readiness levels (TRL; see Annex 1). Operating efficiency is included because it is important to competitiveness in balancing markets, although it is less important for applications with less frequent dispatch, such as back-up power for consumers. Response time and cycle life are included because these are important for some applications, for example ancillary services that require a fast response and frequent cycling.

Energy storage applications can broadly be broken into (1) energy applications (large volumes of energy

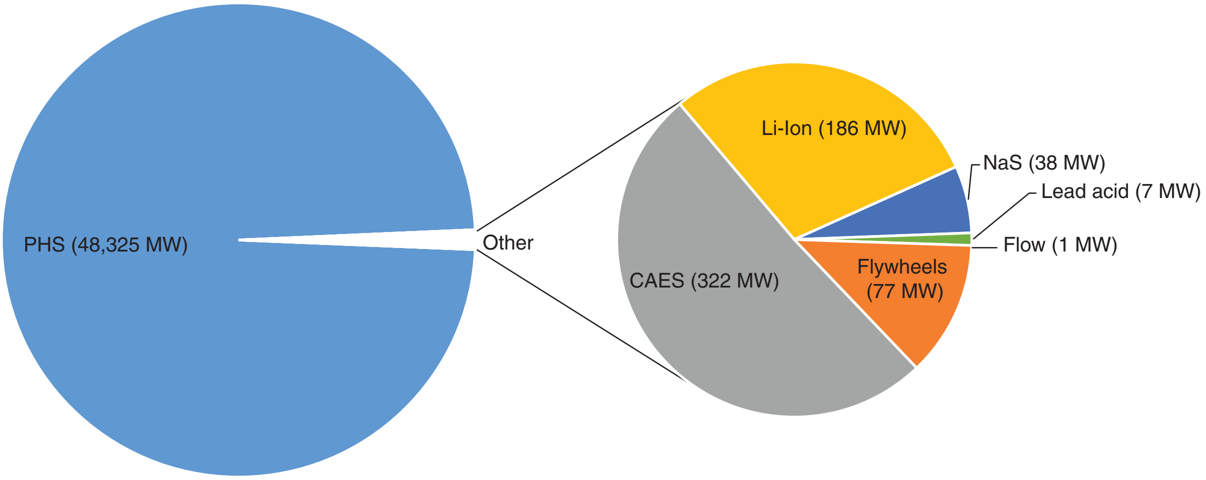

Figure 2.1 Operational grid-connected electricity storage capacity in EU28+Norway+Switzerland (DOE 2016a). Note: data were exported from DOE database in September 2016. Specialised applications of high-power flywheels in the UK and German fusion research laboratories and the RWE Adele Compressed Air Energy Storage (CAES) plant (which is not operational) were excluded.

Table 2.1 Key features of electricity storage technologies and their deployment (September 2016)

Technology	TRL level	Typical power capacity per plant (MW)	Installed power capacity (MW) worldwide	Installed energy capacity (MWh) worldwide	Installed power capacity (MW) in EU28+NO+CH	Installed energy capacity (MWh) in EU28+NO+CH	Number of grid connected systems working in EU28+NO+CH	Typical Duration at rated power	Speed of response	Cycle life	efficiency
Pumped hydro (PHS)	9	100's MW	164,629	(a)	48,325	(a)	157	hours	seconds to minutes	n/a	70 - 80%
Compressed air (CAES)(b)	8	100's MW	437	4,013	322	646	3	hours	minutes	10,000	~ 50%(c)
Flywheels(d)	8	10's MW	144	22	77	6	12	seconds - minutes	milliseconds to seconds	>100,000	90%
Li-Ion batteries	9	up to 10's MW	1,134	1,321	186	343	34,103(e)	minutes - hours	milliseconds to seconds	100,000	85 - 90%
Na-S batteries	9	up to 10's MW	189	1,273	38	296	6	hours	milliseconds to seconds	5,000	70 – 85%
Lead acid batteries	9	up to 10's MW	110	131	7	8	15	minutes	milliseconds to seconds	1,000	75 - 90%
Flow batteries	7	up to 10 MW	74	256	1	5	16	hours	milliseconds to seconds	100,000	70-85%
Power to gas to power	7	100's MW	n/a	n/a	n/a	n/a	n/a	days	seconds to minutes	n/a	~50%

Notes: storage deployment data are from DOE database in September 2016 (DOE, 2016a). (a)Energy capacity data (in megawatt hours) for PHS are incomplete in DOE database. (b)RWE Adele project (Germany) has been excluded because it is not operational. (c)Future adiabatic plants may be more efficient (see below). (d)Flywheel data exclude 400 MW at the Joint European Torus (UK) and 387 MW at Max Planck (Germany) fusion laboratories. (e)Total includes 34,000 household systems (@ approximately 2 kW) in Germany.

dispatched over long time frames, requiring both large power capacities and discharge durations) and (2) power applications (high power over short time-scales), which are discussed further in Chapter 3. The characteristics of the different storage technologies determine their suitability for the different applications.

The focus of this report is on those storage technologies that are already commercially available or will be commercially available by 2020 and are therefore already at or close to technology readiness level TRL 9. However, given the recent revival of interest in electricity storage, which is resulting in major new research and development efforts, including in the EU Horizon 2020 programme, those storage technologies that EASAC considers to be currently below TRL 9 but might reach that level by 2030 are also discussed. Much of the ongoing research is aiming to reduce the costs and to improve the performance of those storage technologies that are close to commercial exploitation.

For this report, heat storage, power to gas, and the charging of battery electric vehicles (BEVs) are considered to be non-dedicated storage and/or more broadly demand response, while the future possibilities of power to gas to power and 'vehicle-to-grid' (electricity fed back into the grid from BEVs) are considered as dedicated electricity storage.

2.1.1 Storage technologies that are or will be commercially available (TRL 9) by 2020[1]

Pumped Hydroelectric Storage (PHS). This technology represents more than 98% of the installed capacity of large-scale electricity storage in the EU and worldwide. It is the most mature electricity storage technology for use in grid-connected applications, having large energy and power capacities and round-trip efficiencies in the region of 70–80%. Historically PHS has been connected to transmission networks and used for load levelling by pumping water to a higher reservoir when demand is low and releasing water to a lower reservoir to generate electricity to meet peaks in demand.

The main advantages of PHS are that it can respond more quickly than most thermal generating plants, and is an excellent provider of reserve and a valuable resource for system balancing. It can also offer black start capability (the ability to begin operation from shutdown without a network connection).

The limited growth in the deployment of PHS in recent years reflects its disadvantages and the challenges involved in expanding its use, which include the economics, the limited number of untapped sites,

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[1] EASAC estimate.

financing the very high capital costs involved, and securing planning and environmental impact approvals for such major construction projects, which typically take years to build. In addition, reduced price spreads lead to insufficient arbitrage profits for private operators (see Chapter 3).

The capacity of PHS in 2015 in the EU28 was approximately 45 GW of power with about 602 GWh of energy. Estimates of the future potential for PHS in the EU have been made in several studies (JRC, 2013; Geth *et al*., 2015), which have concluded that there is a long-term potential for between 3.5 and 10 times the existing PHS capacity in the EU, but no more than about 30 GW of additional PHS could realistically (recognising economic, environmental and other constraints) be added by 2030. In other words, the potential for PHS in the EU28 (including that installed today) is unlikely to exceed about 75 GW by 2030.

Compressed Air Energy Storage (CAES). Experience with this technology has come mainly from two large-scale plants connected to transmission grids (one in the EU and one in the USA): the first was the Huntorf plant (with a capacity of 321 MW over 2 hours) built in 1978 in Germany; the second was the McIntosh plant (with a capacity of 110 MW over 26 hours) built in 1991 in the USA. These two plants operate by storing energy in underground caverns in the form of compressed air and then releasing the stored energy by feeding the compressed air into a gas turbine cycle for electricity generation, thereby bypassing the compressor stage.

Such plants have the advantage that they can be used for several applications including short-, medium- or long-term storage, and for voltage and frequency control (although this may be limited because of their relatively slow response times). A further seven CAES plants have been brought on line in the USA and the EU in recent years, but these are much smaller and mainly used for demonstration purposes (DOE, 2016a).

Important disadvantages are that the number of suitable sites for large-scale underground CAES plants is limited and their round-trip efficiencies are low compared with other storage technologies (the two large-scale plants operate with efficiencies of 42% and 54%). Also, because of the limited deployment of large-scale plants, technology risks still exist, and lessons can be learned from a failed porous rock development in Iowa (SANDIA, 2012). A study for a new CAES plant in Larne, Northern Ireland, was approved in 2015 as an EU PCI, and work on this is ongoing. Research (approximately TRL 6) is continuing to develop adiabatic CAES plants with improved efficiencies of up to 60% (Hartmann *et al.*, 2012), in which heat from the compression stage is stored and recombined with the compressed air during discharge, eliminating the need for an additional fuel source.

Flywheels. Experience with the application of this technology is largely based on its implementation by electricity users, but it is also being used by utilities to provide frequency regulation services to the grid.

Important advantages of flywheel technology are that it has the potential to offer long lifetimes with low maintenance, and can operate over many (>100,000) cycles.

Its main disadvantage is that, while its energy efficiency can be as high as 90%, its self-discharge rates are also high, so it is best suited for ancillary service applications with short cycles. Typical discharge durations range from a few seconds up to 15 minutes, and power ratings from kilowatts to 20 MW. Two 20 MW plants are operational (in the USA), providing frequency regulation (SANDIA, 2014).

Commercially available batteries (TRL 9). Batteries have been used for many years to provide uninterruptible power supplies (UPS) and energy storage in applications involving micro-grids and/or networks on small islands.

Important advantages of batteries are that they can respond quickly (milliseconds), which makes them attractive for providing voltage or frequency control and reserve services in large networks where a fast response time is required.

The main disadvantages of using batteries in grid-connected storage applications are their relatively high costs and limited cycle lives.

- *Lead–acid batteries.* These have been widely used for many years in stationary applications. They are still used worldwide for uninterruptible power supplies and, together with small PV generators, for off-grid solar home systems. A few large-scale systems are used for load levelling in the USA. The most reliable lead–acid batteries for use in remote applications are deep discharge tubular plate designs. However, these are likely to be replaced by newer technologies as they become more competitive (for example OCSM[2], with copper as core in the electrode grid, and OPzV[3], with gelled electrolyte, offer good cycle stability in stationary applications).
- *Nickel–cadmium batteries.* These have been widely used for remote stationary applications, where they provide uninterruptible power supplies and power quality services. However, since 2006, the use of

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[2] OCSM is an abbreviation for 'Ortsfestes Kupfer (Cu)-Streck-Metall' (expanded copper sheet).

[3] OPzV is an abbreviation for 'Ortsfeste Panzerplatte Sonderseparation mit Vlies'.

cadmium-based batteries in the EU has been restricted by the EU batteries Directive (2006) for environmental reasons (the toxicity of cadmium) and they are likely to be replaced in the future by other battery technologies.

- *Lithium-ion (Li-ion) batteries.* These are being increasingly deployed in grid-connected applications as well as in BEVs. They offer good efficiency, a relatively good cycle life, limited calendar ageing (with controlled state of charge), low maintenance and relatively low self-discharge. In grid applications, a typical battery system currently delivers up to tens of megawatts and typical discharge durations of a few hours. Around 1130 MW of grid-connected installations are currently (2016) operating worldwide, and there are almost 40,000 small (average 6.25 kWh) household systems in Germany, making a total deployment of more than 200 MWh of Li-ion batteries in household systems), but larger systems (several hundreds of MWs) are also being contracted/built for demonstration.

  The global production of Li-ion batteries is evolving fast and is expected to increase beyond 250 GWh per year by 2020, which would be triple that produced in 2015 (Enerkeep, 2016). Many of the new Li-ion batteries, which will be produced over the next few years, will be sold primarily for use in BEVs, but larger cells are being developed for dedicated grid-connected storage systems, and it seems likely that many GW of Li-ion batteries will be installed in grid-connected applications worldwide in the next few years.

- *Sodium sulphur (NaS) batteries.* These have been operating since the late 1970s, largely on the basis of technology manufactured in Japan. However, their operating temperature of 300 °C brings a heat management requirement which, for efficiency reasons, implies that they are only viable in large-scale applications with high levels of utilisation. It is noteworthy that at an installation in Japan, which was used on the grid, a major fire highlighted the need for important safety enhancement measures (NGK Insulators, 2012). On the other hand, the main battery materials (sodium and sulphur) are readily available worldwide, so the technology will not suffer from the long-term material resource problems that are faced by some other battery technologies.

2.1.2 Storage technologies at TRL less than 9, possibly commercially available by 2030[4]

Power to gas to power (P2G2P). This technology has potential for use in seasonal storage applications. It has the advantage of low self-discharge, but also the disadvantages of low round-trip efficiencies and high costs.

Several P2G2P technologies are being investigated for using electricity to produce synthetic natural gas, which can be stored and used later. A growing number of pilot projects in different EU countries has been funded in recent years, but none has yet been proved in mainstream commercial deployment. The most widely studied P2G process employs electrolysis to produce hydrogen, which may then be converted by methanation of carbon dioxide into synthetic natural gas and stored in the natural gas grid. The gas can be converted back into electricity (P2G2P) but, because of the many conversion processes involved, this path typically suffers from low round-trip efficiencies and high costs. Nevertheless, it is one of the few options that can offer high volume seasonal energy storage. Significantly improved round-trip efficiencies can be obtained if hydrogen is directly used for re-electrification in efficient H_2–O_2 fuel cells, with efficiencies in excess of 60% predicted after further development (Büchi *et al.*, 2014).

Cryogenic energy storage. This technology stores electricity by liquefying gases (for example air, nitrogen, natural gas or organic fluids) at low temperature (liquid nitrogen is stored at about −196 °C), and later releases the gas through a turbine to generate electricity. Liquid air energy storage (LAES) systems have the potential to be significantly smaller than compressed air storage systems because the volumetric energy density of liquid air (over 660 MJ per cubic metre) is considerably higher than that of compressed air (approximately 60 MJ per cubic metre at 100 atmospheres). Liquid air energy storage can use existing air liquefaction and gas infrastructure, and offers a relatively long storage duration (hours to weeks) with a relatively short response time (approximately 2.5 min). In addition, it has a high cycling ability with an expected life span over 20–40 years, and minimal degradation in terms of depth-of-discharge. However, independent systems have a modest round-trip efficiency of below approximately 60%, so work continues on the development of heat recovery systems and integration with nearby sources of waste heat. Liquid air energy storage systems are likely to be sized in tens or hundreds of megawatts to allow the use of commercially available liquefaction technologies, and to operate near to large-scale sources of waste heat to maximise their operating efficiency. A 350 kW/2.5 MWh pilot plant was built in 2011, and a larger demonstration plant rated at 5 MW/15 MWh is scheduled to be operational in mid-2017 (Highview Power Storage, 2016).

Super capacitors. These can be used for high-power, low-energy applications that require a rapid response, and recent applications include hybrid systems in which they work together with batteries. They have the advantage of an excellent cycle life (millions of cycles),

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[4] EASAC estimate.

but the disadvantages of having a low energy density compared with batteries, and of currently not being cost competitive with other options for medium- or large-scale energy storage in electricity networks. Approximately 28 large grid-connected systems are operational worldwide, many of which are connected to railway or metro systems for regenerative breaking (DoE, 2016a).

Superconductive magnetic energy storage. These devices employ a superconducting coil, a power conditioning system and a cooling system to chill the coil below the superconducting transition temperature. They are potentially well suited for power quality applications because of their high cycle life and power density. Their main disadvantages for grid-connected applications are currently their low energy density and high costs.

Batteries still under development (TRL<9).

- **Sodium ion (Na-ion) batteries.** This technology is still at a relatively early stage of development. The use of sodium has the advantage that it offers greater availability of materials than for the equivalent Li-ion battery. In addition, Na-ion batteries can use aluminium current collectors, which are cheaper than the copper, which has to be used for negative electrodes in Li-ion batteries. Moreover, although Na-ion batteries have only recently (2016) been demonstrated beyond the laboratory, they are expected to have lower costs. Their manufacture is very similar to that of Li-ion, which may hasten their commercialisation compared with that of other batteries.

- **Flow batteries.** These batteries comprise a stack of cells and two tanks. The power capacity of the battery depends on the design of the stack, while its energy capacity depends on the size of the tanks. Redox flow batteries can use various electrochemical couples including vanadium–vanadium, zinc-bromide and iron–chromium. They have the advantage of offering multi-hour cycles, long lifetimes and manageable self-discharge. Vanadium systems have the disadvantage of high electrolyte costs, while the costs of mixed acid vanadium systems may be lower (Vionx, 2016). Research into organic polymer-based redox flow battery systems in Germany and in the USA has recently been making good progress (Janoschka *et al.*, 2015; Aziz, 2016).

2.1.3 Non-dedicated storage–comparators, commercially available (TRL 9) by 2020[5]

While non-dedicated storage is not the focus of this report, some options are discussed below and serve as comparators (O'Malley *et al.*, 2016).

Power-to-heat. This technology can offer value in grid management applications, because it is a relatively low-cost means of storing excess electricity, which has the advantage of potentially reducing the need for curtailment of grid-connected electricity generators. However, it has the disadvantage that the electricity, which has been converted into heat, cannot be returned to the grid cost-effectively.

Electricity that has been converted into heat can be used for space and/or water heating in buildings, either directly or via district heating systems. Traditionally, electric heating systems have been used either in areas with large supplies of hydro power, such as in Scandinavia, or with large supplies of nuclear power (such as in France). The electricity can either be used for resistive heating in storage heaters and water tanks, or deployed through heat pumps. The conversion of electricity to heat in ceramic storage heaters or in low-temperature water tanks at less than 100 °C involves well-established technologies, which can be further exploited in future to allow variable renewable electricity to be valued and used instead of being 'dumped' when its generators (mainly wind or solar PV) are subjected to curtailment. As the size of the heat sector in the EU is approximately twice the size of the electricity sector (EC COM (2016) 51), heat could serve as a sink for 'excess' (that is, otherwise curtailed) wind and solar electricity for much larger capacities of variable renewable electricity generation than is currently installed. However, the economic value of power-to-heat depends on the prices of the other heating options that are available in the area. For example, high temperature heating supplied using solid, liquid or gaseous fuels may be expensive compared with low-temperature heating supplied using waste heat from power generation or industrial processes.

Power to gas (P2G). In contrast to dedicated electricity storage using P2G2P, which was discussed in section 2.1.2, converting power-to-gas (P2G) but not back to power again is already technically viable, and less expensive (for example using synthetic natural gas in vehicles or directly in industry). Consequently, a growing number of pilot plants are under construction or in operation across the EU (Markillie, 2016). P2G technology has the advantage of a widely recognised potential for contributing to decarbonisation of the transport sector, but disadvantages that there are major challenges to overcome both in establishing a viable new fuel supply infrastructure and in converting the EU vehicle fleet to use new fuels.

Battery Electric Vehicles (BEVs). These are a special application of non-dedicated grid-connected electricity storage which uses high-quality batteries. It has the

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[5] EASAC estimate.

advantage that the costs of the batteries can be partly offset against the benefits of mobility, but potential disadvantages that the battery may not be connected to the grid when it is needed, and that energy may be demanded to charge the battery for mobility purposes at times when grid electricity is in short supply.

The amount of electricity used by a BEV to travel the average distance covered by a typical family car (13,000 km per year, or 35 km per day) is between about 6 and 8 kWh per day, while the capacity of the battery packs in the currently available BEVs varies between about 20 kWh for the smallest BEVs to approximately 90 kWh for the largest (Tesla, 2016). (Such approximate data on battery packs are released by vehicle manufacturers and collated by Battery University, 2016.)[6] In comparison, the average electricity consumption of a typical European household varies between about 5 and 10 kWh per day (Odyssee-Mure, 2014), which is less than the unused BEV battery capacity on an average day for a typical householder. It is therefore not surprising that interest is growing in the potential for using the batteries in BEVs also to contribute to self-consumption in households. For example, with appropriate market signals, when BEVs are stationary at home or the owner's work place or in a car park, they might store electricity during periods of over-supply, and feed electricity back into the home of its owners or to the distribution grid during periods of high demand.

The potential for deploying used BEV batteries, after they have been removed from BEVs, (the so-called second life) to provide low-cost storage for grid system balancing, is being explored because BEVs have generally higher battery quality requirements than would be needed for stationary applications. However, this frequently proposed approach risks potential problems related to cell balancing in large-scale 'used' battery installations (Meisel *et al.*, 2013), and difficulties related to measuring the quality of used batteries (research into possible test methods for Li-ion batteries is ongoing and challenging) (Martinez *et al.*, 2017). In addition, the long-term viability of second-life batteries will be influenced by the recycle value of the materials and the size of the available balancing market. From an economic point of view, second-life applications may have a role in the future (Rezania and Prüggler, 2012), but the extent of that role is not yet clear.

2.2 Storage technology costs

2.2.1 Overview

One of the most commonly stated reasons for not installing more storage on electricity grids is the poor cost–benefit ratio of storage relative to its competitors, and much of the ongoing research on electricity storage is focused on cost reduction or on performance improvements with the aim of achieving better cost-effectiveness.

From an investor's perspective, it is risky to generalise about the costs of the different storage technologies because costs depend on the application and on the local situation in which the storage is deployed. For example, it may be feasible to reduce the costs of storage so that it can become competitive for some applications, such as short-term balancing but, as discussed above, it may still not be competitive for delivering energy over longer periods. Moreover, some storage technologies may be competitive for very high-power applications over short time periods, but not for large-scale energy storage. Many electricity storage technologies are still at the pilot or demonstration stage of development, and are not yet manufactured for applications at utility scale, so their future costs in large-scale deployment are not yet known.

It is important when comparing energy storage technologies that entire system costs are considered because the energy storage device typically makes up only between 25% and 40% of the total system costs (Gyuk, 2014). For example, costs for battery technologies are often quoted on the basis of the pack only, with additional costs such as the power conditioning system, control system, site works , etc. omitted.

System modelling allows cost comparisons to be made in which the size of the storage is optimised, and the relevant storage design parameters are taken into account, including part-load performance, round-trip efficiency, self-discharge rate, storage cycling performance, plant lifetime, operation and maintenance costs, disposal/recycling costs, as well as the present and future market conditions. The use of system modelling studies to address the cost–benefit analysis of energy storage is discussed in Chapter 4 but, in view of the many uncertainties and risks of causing confusion listed above, tables of different storage system costs are not presented in this report. Instead the future trends that are expected in the different storage system costs and the reasons for these future trends are presented below. In addition, because of their very rapid market growth over the past 2–3 years, some recent information on the costs of Li-ion batteries is highlighted in Box 2.1 below.

2.2.2 Costs of technologies that are or will be commercially available (TRL 9) by 2020

Pumped hydroelectric storage (PHS). This is a mature technology which is already widely deployed

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[6] Similar compilations of vehicle manufacturers' data in private communications with ISEA, RWTH University of Aachen, indicate that the energy consumption of current BEVs is typically about 20 kWh per 100 km.

and is likely to be the most cost-effective option for large energy capacity storage where suitable sites and transmission network connections are available. However, PHS typically involves very high capital investments because of its large physical size. In comparison with most other electricity storage technologies, PHS has a lower capital cost to energy capacity ratio, as well as a reasonably good round-trip efficiency. However, the potential for further cost reductions for PHS systems is limited.

Compressed air energy storage (CAES). Field experience with CAES is largely based on that from the two plants that have been operating for more than 25 years, which suggests that the potential for further significant reductions in capital costs is limited. Nevertheless, CAES may become competitive in areas without access to sites for PHS. Adiabatic CAES will increase the initial capital costs, but is expected to deliver higher operating efficiencies, and therefore to improve overall cost-effectiveness (De Samaniego Steta, 2010). New cost data can be expected to result from some of the smaller plants that have recently been built (DOE, 2016a) and from the ongoing PCI study in Larne, Northern Ireland (EC, 2015c).

Flywheels. Flywheels are used in a wide range of industrial applications so their costs have already benefitted from some economies of scale, despite the fact that they have not yet been widely used to provide ancillary services to the grid. Growing interest in flywheels for grid applications in recent years and the emergence of new technology providers in the EU can be expected to lead to further cost reductions.

Costs of commercially available batteries (TRL 9)

- *Lead–acid batteries.* The simple flat plate designs used for automotive applications are mass produced all over the world at very low prices, but have short lifetimes and relatively poor performance in stationary applications. In contrast, the deep discharge tubular plate designs, which have much longer lifetimes, are significantly more expensive because of more material usage and a relatively high number of different products on the market (lack of standardisation).

- *Lithium-ion batteries.* Li-ion batteries are being increasingly used in BEVs, where their costs have dropped faster and further than most experts predicted, largely because of a combination of economies of scale and worldwide over-capacity of production compared with the current market size (see Box 2.1).

2.2.3 Overview of expected future trends in the costs of electricity storage technologies

Based on the available evidence, which is summarised for each of the technologies above, an overview of the trends for future cost reductions is presented in Table 2.2 for each of the main electricity storage technologies. In this table, it can be seen that those technologies that appear to have the highest potentials for cost reductions are batteries.

The data from the references listed in the legend to Figure 2.2 reflect the views of many experts in the field that Li-ion battery costs will fall to €150–€250 per kilowatt hour by 2020.

2.3 Further research and development on storage technologies

Further research work is required on reducing the costs of those dedicated storage technologies with significant potential for cost reductions in grid applications. In addition, it will be important to continue pursuing technological advances for such storage systems because their key characteristics are not necessarily well matched to those of storage systems that are used for BEVs (for example requirements for energy density and cycle life differ significantly between dedicated electricity grid applications and those for BEVs).

Table 2.2 Potential cost reductions for storage technologies

Technology	Potential for future cost reductions
Pumped hydroelectric storage	Low
Compressed air energy storage	Medium
Flywheels	Medium
Lead–acid batteries	Low
Li-ion batteries	High
Sodium ion batteries	High
Redox flow batteries	Medium/High
Sodium sulphur batteries	Medium
Super capacitors	Medium
Power to gas to power	Medium
Cryogenic energy storage	Medium

BOX 2.1 Recent developments in lithium-ion battery prices

The current call price of Li-ion batteries for transport is between €200 and €300 per kWh, which is very much lower than the prices of €400-500 per kWh which were widely anticipated by storage experts in 2016 (see Figure 2.2).

Further to the recent falls in Li-ion cell prices, new technological developments and substantial economies of scale from larger production plants are expected not only to bring costs down even lower, but also to improve performance as the global markets for Li-ion batteries continue to grow.

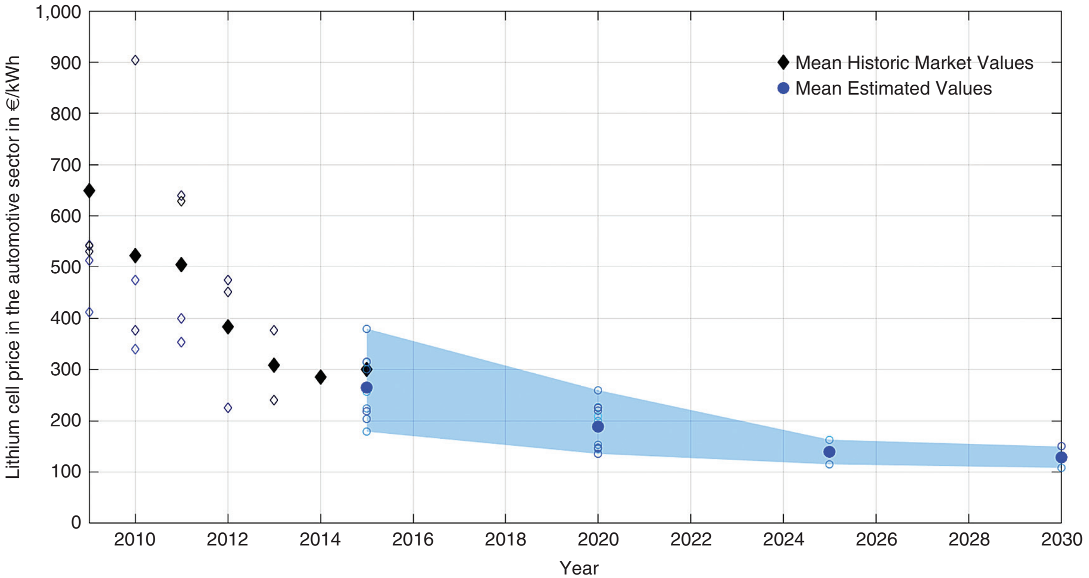

Figure 2.2 History and future projections of prices for Li-ion batteries. Courtesy of Julia Badeda, ISEA-RWTH Aachen, Germany, on the basis of data from Deutsche Bank (2009), BCG (2010), Roland Berger (2010), TIAX 18650 (2010), CE Delft (2011), AT Kearney (2012), Roland Berger Automotive [Ber12a] (2012), Roland Berger Lithium [Ber12] (2012), Element Energy [Clu12] (2012), Avicenne (2013), Roland Berger (2013), ISI (2013), MW Group (2013), Navigant (2014), ISI (2015), UBS (2014), UBS-A (2014).

3 Services offered by storage to EU electricity markets

Electricity storage facilitates the decoupling of electricity supply and demand, and can be used to provide a wide range of ancillary services. As shown in Figure 3.1, different storage technologies can be deployed at different voltage levels in the electricity system, providing a range of services and operating in several markets.

Most of the storage on the EU transmission networks today was installed in the 1970s and 1980s to accommodate rapid variations in demand (storage added flexibility to the system), and/or because of price spreads between nuclear, coal and oil-fired generation. At that time, storage was particularly valuable to systems with large capacities of inflexible baseload plant, where it increased capacity factors during the night and reduced the need for expensive peaking capacity during the day. In the following two decades, more flexible generating plants (typically gas fired) were added to many of the EU electricity systems, so there was little need for the construction of new storage systems.

More recently, over the past decade, the increasing penetration of variable renewable electricity into the EU electricity system (notably from wind and solar PV) has been changing the roles and markets for some existing storage systems but at the same time opening up new roles and opportunities for storage. For example, solar PV now contributes to meeting the midday peak in Germany, which reduces prices and therefore has a negative impact on the profitability of using large-scale storage for energy arbitrage (Endbericht FfE, 2014). At the same time, in some areas with a cluster of solar PV systems, distributed storage systems are being deployed to allow higher levels of self-consumption while at the same time reducing local congestion on distribution grids (Kairies *et al.*, 2015).

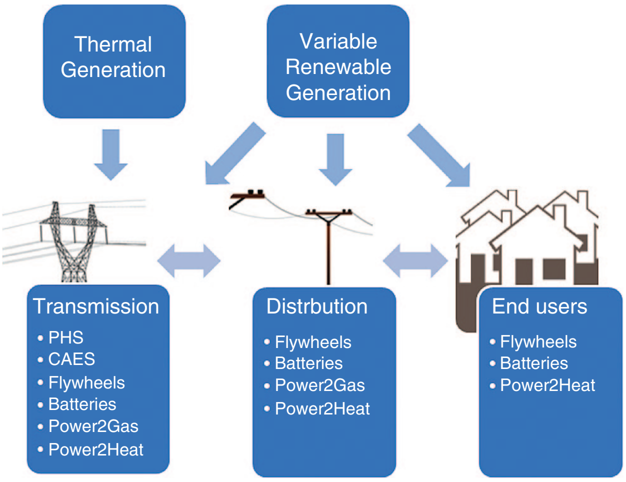

Figure 3.1 Storage technologies in EU electricity grids.

A highly flexible electricity system would have a very limited requirement for energy storage or for its competitors that provide added flexibility. However, for the foreseeable future, EU electricity systems will continue to face many challenges in relation to flexibility as the fraction of variable renewable electricity increases. This is particularly challenging for isolated or weakly connected systems, and for systems with large shares of inflexible thermal plant. Storage can usually participate in existing markets for energy and ancillary services, although some barriers exist and there are some key design issues that need to be addressed to ensure that the most cost-efficient solutions are incentivised from the range of potential flexibility options.

Increasing system flexibility (including the use of dedicated storage) can reduce the need for peaking generating plant and increase the capacity factors of baseload plant. It can also reduce the numbers of starts and ramping required of thermal generating plants, thereby reducing the operating and maintenance costs of generation (Denholm *et al.*, 2013; O'Dwyer and Flynn, 2015). At times when renewable power generation exceeds local demand and there is insufficient network capacity to export the surplus energy to another region, dedicated storage can reduce the need to curtail wind and/or PV generators. Also, in some isolated systems, variable renewable generation may need to be curtailed by the system operators to avoid instability at a system level because a percentage of synchronous generation is required to maintain stable operations (O'Sullivan *et al.*, 2014).

Balancing markets (which run concurrently with the energy markets) are used by transmission system operators to maintain a supply/demand balance in real-time (after gate closure). Balancing requirements are highly dependent on energy market design because intraday trading in energy markets allows adjustments to schedules closer to real-time (for example energy markets with continuous intraday trading and short gate closure times have low balancing requirements compared with markets that are dominated by day-ahead trading). This is particularly important for systems with high penetrations of variable renewable electricity generation, because variable generation is not totally dispatchable and naturally involves forecast errors.

In the future, there will be growing opportunities for the introduction of specific markets for *short/medium term flexibility*, in which all potential providers including dedicated electricity storage, non-dedicated storage, demand response and flexible generators can compete with an even chance of success (on a 'level playing field'). Several market products have already been identified as possible ways to implement new markets in flexibility, including 'inertia' and 'ramping' products (EirGrid, 2016), as well as 'enhanced frequency response' services (National Grid, 2016). Each case will be different from a cost and business perspective but, from a technological perspective, dedicated electricity storage could be a competitor with thermal generation in flexibility markets, and thereby significantly reduce curtailment, despite the fact that the ramping capability of generators continues to improve, including that of nuclear generators (Strbac *et al.*, 2012). The demand for electricity may also evolve in future through the uptake of new technologies and practices, which may open up new opportunities for providing flexibility services.

The ability of a given storage technology to provide the various services required by the grid depends on the specific characteristics of that storage technology. For some services, large energy and power capacities are essential, for example for energy arbitrage or generation adequacy. For other services (for example power quality control and some end-use applications) small energy capacities are sufficient, but other storage characteristics are needed, for example high cycling capabilities or fast response times. The existing and emerging applications of electricity storage are discussed further below.

3.1 Energy arbitrage

Energy arbitrage is the foremost application associated with large-scale dedicated electricity storage on the grid. Less expensive electricity is used for charging the storage, which is later discharged by supplying electricity to the grid during periods of expensive electricity. The ability of the different storage technologies to perform these functions varies depending on their state of charge, their charging/discharging capability, and their energy storage capacity, as well as on the inherent operating characteristics of the technologies themselves.

Energy arbitrage traditionally takes place in day-ahead and 'intraday' time-scales, (charging at night and discharging during peaks in demand on the system), although changes in the net load profile driven by increased penetrations of variable renewables will impact on future storage plant behaviour. The penetration of variable renewable electricity, which has zero marginal cost, can strongly drive down wholesale electricity prices, and therefore reduce the potential profits from energy arbitrage (Barbour *et al.*, 2016). However, at very high penetrations of variable renewable electricity, negative prices and higher volatility can occur, with high prices in times of scarcity of wind and solar energy, which can create new opportunities for energy arbitrage (Wozabal *et al.*, 2015). Electricity storage systems participating in fast energy markets with short intervals and gate closure times will have opportunities to perform energy arbitrage in such volatile settings.

Energy arbitrage is typically associated with large-scale storage at the transmission level. However, arbitrage services could also be offered by storage on the distribution grid, for example if domestic electricity storage were to become more widely deployed and if aggregators were allowed to make this capacity available to the wholesale market. In other words, even if residential storage were deployed primarily with a view to maximising self-consumption, it could have value from a system perspective if exposed to appropriate price signals or incentives (see the paragraph entitled 'Self-Consumption (PV + battery)' in section 3.5).

3.2 Ancillary services

One of the ways that electricity storage can compete with conventional generation is through the provision of ancillary services, which include reserves/frequency control, voltage control and black start capability. Typically, ancillary services markets offer a more profitable role for electricity storage than energy arbitrage, although the need and corresponding size of the market for ancillary services is limited (Fleer *et al.*, 2016, 2017). Some system operators are considering the introduction of new flexibility products as well as inertia provision to meet the more demanding system requirements, which are expected in future as the contribution from large rotating masses in synchronous generators declines (EirGrid, 2016).

Reserves (frequency control and balancing). To maintain a supply/demand balance, all systems must carry a certain volume of spare generating capacity to compensate for any large-scale generator outages or forecast errors that would cause the system frequency to alter. Reserve requirements vary for different systems, and reserve definitions are categorised according to necessary time-scales (i.e response time and duration). Owing to its fast and accurate response capabilities and its high part-load efficiencies, energy storage is well suited to providing a range of reserve categories; for example, battery storage is well suited for providing short response time services such as 'enhanced frequency reponse' (National Grid, 2016). Looking to the future, with higher penetrations of variable renewables, there will be an increased volume of reserves (Ela *et al.*, 2011). In highly developed ancillary services markets such as those introduced by the regional transmission operator PJM Interconnection LLC in the USA, where a strong market for frequency regulation has emerged under US Federal Energy Regulation Commission Order 755, payments are linked to performance. In this instance, a positive business case for energy storage (including batteries) has emerged (Avendano-Mora & Camm, 2015) and investments in electricity storage have been successfully facilitated. However, experience in PJM has also confirmed that the required quantities of such services are limited and that the market becomes saturated quite quickly (DOE, 2016b). While frequency control services in the USA and Europe differ in terms of requirements for deployment, similar opportunities may exist for energy storage in the EU and several commercial and demonstration projects are already ongoing (Fleer *et al.*, 2016, 2017). Sufficient energy capacities and discharge durations are required to qualify for a given reserve category in EU markets. Discussions are continuing in Europe about the harmonisation of prequalification rules for units with limited energy capacity, and the business case in Europe will be strongly impacted by the terms of these rules. Conservative rules, requiring full activation guarantees over long durations, lead to large energy capacity requirements, and therefore weaken the economic viability of many storage systems, for example battery units for the provision of reserves (Koller *et al.*, 2016).

Voltage control. To maintain system reliability, voltages must be maintained within an acceptable range at all points on a system. As thermal generators are replaced, energy storage may be increasingly used to provide voltage support, although variable renewable generators can provide reactive power and hence voltage control, and can play a role in providing some voltage support. Many storage technologies have excellent voltage regulation capabilities, although the effectiveness of pumped hydro is somewhat limited because of its typically remote location (Alizadeh Mousavi, 2011). As voltage management is a local issue and reactive power cannot be transmitted over long distances, distributed storage could play a role in providing voltage support, mitigating the negative impacts of non-dispatchable distributed generation on the distribution grid (Marra *et al.*, 2012; Yang *et al.*, 2014).

Black start. The ability to begin operation from shutdown without the assistance of the power system is an essential ancillary service required for grid recovery in the event of a black out. Many storage technologies are well suited to the provision of black start services including pumped hydro and battery technologies.

3.3 Grid adequacy (for congestion management and network upgrade deferral)

Poor infrastructure can limit the flow of electricity across transmission and distribution networks, and the resulting congestion can lead to curtailment and/or increased generation costs. This challenge continues to arise across the EU because grid reinforcements do not always keep pace with the growth in demand, or with the increasing deployment of distributed generation. The expected increases in distributed generation and in the electrification of heating systems and transport in the period to 2030 will require substantial investments in new network infrastructure at both the transmission and distribution levels.

Electricity storage can be used to manage congestion on the grid and can potentially be used to defer network upgrades. Sioshansi and Denholm (2009) demonstrate increased transmission utilisation and reduced transmission costs by using dedicated storage. Renewable generators co-located with storage can also reduce imbalances, which is important when the generators are subject to balancing responsibilities (Carbon Trust 2016), particularly for small producers that do not have the advantage of balancing across a large portfolio. However, using storage to provide balancing at a local level is inefficient from a system perspective, and the benefits arising from the natural smoothing effect of aggregation on a wider scale are lost. Nevertheless, storage can play a role on distribution grids. The use of distributed battery storage as an alternative to distribution grid reinforcement is described by Nykamp *et al.* (2015), with benefits identified when using a battery for peak shaving, particularly when the battery can be used to temporarily defer an investment, and afterwards be moved to more than one location, thereby delivering a better return on investment for the storage owners. Deferral of network infrastructure investments can be particularly valuable in sensitive regions where it takes a long time to secure planning approvals and where the costs of installation are very high, for example in environmentally protected areas.

Investments in network reinforcements and/or storage to reduce congestion can be incentivised through the pricing of grid bottlenecks. In the USA, this is done by using nodal pricing (Neuhoff *et al.*, 2011), but there is currently no EU-wide agreement on how this should be done in EU markets. As noted in Chapter 1, both grid reinforcement and storage have been included in the lists of EU PCIs, but it is not yet clear how the most cost-efficient investment options should be selected.

3.4 Generation adequacy

Ensuring that sufficient generation is available at all times is an important obligation on system operators (known as generation adequacy). Increases to the adequacy of the power system can be paid for through the energy market or through capacity payments, in those areas where a capacity market has been put in place. Capacity markets are increasingly being introduced across Europe, in regions where there are none, as a precaution to ensure that there is sufficient generating capacity at all times (ACER, 2013). Capacity markets provide compensation for the reduced utilisation and profitability of thermal generation, which is resulting from the rapid growth of variable renewable generation. The most cost-effective way to secure sufficient generating capacity during extended periods when the sun is not shining and the wind is not blowing depends on the specific conditions and the location, but can be addressed to different extents by dedicated storage, interconnections, demand response, non-dedicated storage and conventional generation.

Many storage technologies can offer generation capacity over limited periods and can therefore contribute to generation adequacy, but their capacity value (contribution made to generation adequacy) depends largely on their discharge duration (Sioshansi *et al.*, 2014). Contractual agreements for generation adequacy therefore need to include specific requirements for storage systems that address their limited energy capacities. Although there is over-capacity in many parts of the EU today, generation adequacy may become a more demanding challenge in the future because of a combination of factors, including ageing assets and the phase out of nuclear and coal-fired generators in many regions. While installed capacities of variable renewable generation are increasing, their capacity values are low compared with those of thermal (including nuclear) power generation owing to their low capacity factor (ratio of average power generated to the nameplate capacity) and the non-dispatchable nature of the energy source. Capacity values of variable renewable generation decrease as their installed capacities increase, and the possibility of very low output becomes more important with larger shares of wind and solar energy (Keane *et al.*, 2011), which means that dispatchable plants (in particular large hydro and thermal power plants but potentially also dedicated storage) and/or demand response and/or non-dedicated storage are still required to maintain system reliability. Today, generation adequacy is still largely assessed on a national basis. As interconnections are being reinforced and long-term (10 year) planning by the European Network of Transmission System Operators for Electricity (ENTSOe) also involves the development of European wide adequacy assessments, further steps towards stronger regional and eventually EU-wide cooperation on this must be foreseen.

It should be noted that, while energy storage can contribute to capacity adequacy, and capacity markets may offer an additional revenue stream for storage plant operators, capacity markets could limit the spreads on the spot market to marginal short-run costs and reduce the potential arbitrage profits of a storage plant operator.

Seasonal energy storage (storing energy for periods of weeks or months before discharge) could play a role in future systems with extremely high shares of variable renewable generation and the resulting seasonal supply/demand mismatches. However, for storage to contribute on a meaningful scale to seasonal mismatches, much larger energy storage capacities would be required than for short-term balancing, and storage technologies with a high energy density would be essential. None of the existing dedicated electricity storage technologies other than P2G2P, which is currently too inefficient and far too expensive, has the potential to contribute to seasonal balancing of the grid.

At times of very low variable renewable electricity supply, for example on winter evenings during periods of high atmospheric pressure when wind speeds over an extensive geographical area can be very low for long periods (more than a few days) and there is no solar energy, system demands must be met by other generation, in particular hydro and thermal power plants. While additional storage could contribute to meeting peaks in demand during these periods, storage is not likely to contribute significantly to this challenge owing to the enormous energy (and to some extent power) capacities required (see Box 3.1).

Box 3.1 Notes on potential contribution of dedicated storage to generation adequacy

From the data given in Table 2.1, it can be seen that the power capacity of electricity storage in the EU is currently almost 50 GW. While this represents only about 5% of the total EU generating capacity (1 TW), less than 10% of peak EU power demand (approximately 550 GW) and only approximately 13% of the average EU power demand (approximately 375 GW) (ENTSOe, 2015), it does represent almost 23% of the current levels of variable renewable generating capacity (130 GW of wind and 90 GW of PV (Eurostat, 2016c)), although these levels are expected to grow to deliver the EU target of 27% of renewable energy (approximately 50% of EU electricity generation) by 2030.

When considering the generation adequacy of storage systems, it is also important to address their energy capacity because, as indicated in Table 2.1, storage systems can only supply at their nominal rated power (gigawatts) for a few hours before needing to be recharged.

The total energy storage capacity in the EU28 is currently estimated to be approximately 600 GWh (Geth *et al.*, 2015), which corresponds to about 7% of the daily average EU electricity consumption of approximately 9 TWh (Eurostat, 2016a). Approx 12% of EU electricity consumption (1 TWh per day) was supplied by variable (wind and solar PV) generation in 2014 (Eurostat, 2016d), so the current energy capacity of dedicated storage in the EU is equivalent to little more than half of one day's average variable renewable electricity production.

Taken together, the above data suggest that without massive increases in storage power capacity (gigawatts) and in storage energy capacity (gigawatt hours), dedicated storage will be unable to fill the gap in generating capacity to any significant extent when wind speeds remain low and/or the sun is not shining for periods of longer than a few hours.

3.5 End-user/consumer needs

Power quality/local back-up. Short duration events (milliseconds to seconds) on electricity networks can affect power quality and cause interruptions in service. When such events occur, it is particularly important to protect those loads that are highly sensitive to power quality (for example medical facilities, data centres, precision manufacturing). A storage technology with high power rating (charging and discharging), but relatively low energy capacity is typically needed for such applications. In addition to power quality applications, batteries are often used to provide an uninterruptible power supply, which protects critical loads in commercial and industrial settings by managing the transition from the grid to a back-up supply when there is a failure on the grid (Gurrero *et al.*, 2007). Some consumers use energy storage to provide their own back-up power although, for long durations (more than a few hours), energy storage would normally be an expensive option compared with back-up generators.

Self-consumption (PV + battery). The recent growth in the deployment of small generators (mainly solar PV) by individual householders has triggered interest in self-consumption, which can bring benefits both to the network operator, for example if it reduces peak demands (and therefore peak generation) and to the householder if it reduces their electricity costs. Local battery storage systems are therefore starting to be installed by a growing number of householders alongside their own distributed generators (mainly PV) to increase their levels of self-consumption. However the long-term sustainability of this approach has not yet been demonstrated.

The limited experience with such systems that is available to date (mainly in Germany) suggests that while economic drivers for increased self-consumption play an important role, as PV-battery systems approach ‘grid parity’ (Grünewald *et al.*, 2012), other non-economic drivers are also present (Römer *et al.*, 2015; Kairies *et al.* 2015). The potential for growth in self-consumption is already causing some system operators and policy-makers to consider changes to their tariff structures. This is because the costs of maintaining and operating the network infrastructure are currently covered by a mix of incomes from energy tariffs and standing (network) charges and, with the current tariff structure, those householders with high levels of self-consumption would pay less towards the costs of maintaining the network infrastructure despite still requiring its services.

Electricity storage has a potentially important role in relation to self-consumption, and its value as a household investment could be strongly influenced by any changes in tariff structures. From a network perspective, household storage systems could also be used to reduce congestion on distribution networks, although advanced management strategies (incorporating forecast algorithms) are required to maximise the potential for congestion management. For such strategies to be incentivised (over maximum self-consumption strategies), appropriate feed-in power limitations and feed-in tariffs are required (Moshövel *et al.*, 2015).

Even without installing their own generator for self-consumption, a consumer can install electricity storage between the meter and the loads, and use the storage to schedule their demands from the grid with the aim of reducing electricity bills (demand response; see Chapter 5). However, this is only feasible from a consumer perspective if there is an appropriate tariff structure with time of use/real-time prices, and/or demand power charges and from a system operator’s perspective if appropriate feed-in power limitations are put in place to avoid creating local grid congestion.(see Box 5.1).

3.6 Operation of storage in multiple roles and markets

The value of storage can be increased when it provides more than one service and/or operates in more than one market, for example by providing a combination of ancillary services and arbitrage or network support. However, some services are mutually exclusive, for example if providing two services simultaneously would involve conflicting dispatches. The ability to provide a given service can be constrained by previous commitments, and while the target use of a given storage capacity can be dynamically changed, the optimisation process is a complex task. In addition, further complications arise when potential services from a single asset could be supplied to both the regulated and the competitive parts of the market, because the asset owner may be prohibited from providing both functions. From a policy perspective it is important to allow storage (and other assets) to participate in the simultaneous provision of multiple services, provided it is physically possible to achieve and can be verified. Furthermore, while system operators are generally prohibited from owning and operating generating assets, they are also typically uniquely positioned to optimise the multiple value streams of dedicated energy storage, particularly in relation to infrastructure support. There is therefore a case for revising the asset base regulation to permit system operators some measure of contractual and regulatory flexibility so that they can respond more efficiently to the evolving system management challenges (IEA–RETD, 2016).

4 Modelling and assessing the values of electricity storage

Computer models have been widely used to assess the values of storage, in particular system configurations and the extent to which storage can contribute to meeting the different system needs under different market and regulatory regimes. While there were no resources available within this EASAC work to perform new computer modelling studies, much can be learned from the peer-reviewed work that has been published by others.

Some of the key lessons that can be learned from the peer-reviewed modelling work in relation to the values of storage are summarised below. Potential changes that might be made to electricity market designs and related policies to give equal opportunities to all technologies including dedicated storage are also highlighted. However, it should be noted that all modelling work has limitations: see section 4.3.

4.1 Modelling methodologies used for valuing storage

4.1.1 Overview

Two modelling approaches are widely used, as electricity storage can be valued from two different perspectives, namely (1) the overall system performance perspective ('system models') and (2) the specific investor perspective ('storage-centric models'). Both modelling approaches can be used to provide evidence of the value of dedicated electricity storage in electrical power systems. This value can be assessed from the perspectives of market design (energy and ancillary services markets, capacity market, network charges , etc.) and related policies (including operating policies).

4.1.2 System models

Depending on the objective, a variety of system model types exist, with differing sector boundaries and structures (Zucker *et al.*, 2013). Examples include energy system models (entire energy system, including both investment and operational optimisation, often over long periods), market models (electricity system models optimising the operation of power plants, often with a simplified representation of the grid) and network models (focusing on network management, often with a restricted time resolution and/or restricted to a specific section of the grid such as transmission or medium/low-voltage distribution with standardisations).

Market models are typically used to minimise costs for the operation of the entire electricity system, including any dedicated energy storage. This allows the impact of a storage device on the wider system to be captured, including dispatch decisions, emissions, operating costs, variable renewable curtailment levels, electricity prices, etc. Storage value can be assessed by completing simulations with/without additional storage and comparing operating costs. Similarly, with sufficient cost and performance data, competing sources of flexibility can be considered by using alternative scenarios of competitor deployment.

Alternatively, investments into dedicated storage and its competitors can be determined endogenously by the system model. The use/application of energy storage technologies can be optimised, while maximising the efficiency of system operation, deferring the need for and/or reducing the costs and optimising the mix of investments in network and generation infrastructure (for example nuclear, carbon capture and storage, and renewable generation) to achieve cost-effective solutions (Strbac *et al.*, 2012, 2015).

Modelling the many different services that dedicated storage can provide is not always straightforward, especially when trying to address multiple simultaneous service provision (for example energy arbitrage, ancillary services, capacity and self-consumption, or grid support with deferral of investments). Different models may be needed: for example one model to assess the system-wide benefits of storage, and another to assess the benefits that storage can bring to a local distribution system.

4.1.3 Storage-centric models

These models maximise the revenue stream/profits of an energy storage device that provides a range of system services (energy arbitrage, frequency regulation, congestion management , etc.), within a particular market design.

They provide important information and trends from an investors point of view. However, the investor perspective typically is very dependent on the specific market design (including taxes , etc.), so such valuations are highly exposed to regulatory risk. This can also imply that the use of storage is not optimal from a system operation point of view.

The price taker approach is typically used, which assumes that the device is not large enough to have an impact on market prices, although feedback functions can be used to take price effects into account. Also, it is often assumed that prices can be forecasted perfectly, which tends to overestimate plant profitability, particularly in highly variable renewable electricity scenarios with increased price volatility. Approaches such as dynamic and stochastic programming and Monte Carlo simulations can be used for applications in more volatile markets, although these have significant computational and data requirements.

4.2 Value of storage and findings from modelling assessments

There are many studies in the scientific literature that are based on different scenarios for the development of technology, electricity consumption, economy, operating policies and market conditions, as well as the services provided and the placement of storage (that is, distributed or centrally placed). The results of each study are, of course, applicable only for the selected scenarios, but by bringing together the results of many studies, some trends can be identified. The roles and opportunities for flexibility, including dedicated electricity storage and its competitors, grow as the penetrations of variable renewable generation increase on the power system (IEA, 2014). Some important findings are highlighted below.

Storage to reduce variable renewable energy curtailment. Energy storage is often proposed as a means to reduce renewable generation curtailment. However, owing to the currently high costs of storage, including capital and operating costs (that is, losses), the reduction of variable renewable energy curtailment alone has generally not yet been found to be economically viable (Nyamdash *et al.*, 2010), although the business case improves when considered alongside other applications (see next paragraph, 'Storage for multiple uses'). Alternative options, such as network reinforcement, can be more cost-effective (Doering, 2015; EWI, 2011) than dedicated storage. However, network expansion is a lengthy process, which often faces significant opposition, so optimal network development may not be achievable. The curtailment reductions achieved by storage can be effective in reducing carbon dioxide emissions from the electricity sector (Totschnig *et al.*, 2015). However, as storage can also be used to increase capacity factors of baseload plant, systems with large capacities of coal-fired baseload may see increases in emissions with the introduction of additional storage (Tuohy and O'Malley, 2011). The results, in terms of both costs and emissions, are driven by carbon and fuel price assumptions. High carbon dioxide prices also increase market price spreads, which increase the value of storage (Bertsch *et al.*, 2016).

Storage for multiple uses. The importance of operating storage in multiple roles has already been discussed in section 3.6. Not surprisingly, the value of storage increases significantly when storage is used to provide multiple services, with the benefits aggregated (EPRI, 2010; SANDIA, 2010). However, many of the value streams highlighted in US reports do not currently apply in the EU because the market designs and system configurations are different: for example, performance payments for frequency regulation, financial transmission rights at nodes with high prices (requires nodal pricing) and capacity payments (Zucker *et al.*, 2013) do not currently feature significantly in EU markets, but such combinations may emerge in the EU as its future market designs evolve. While multiple value streams exist for energy storage, it cannot be assumed that the results from different studies are cumulative unless they have been optimised simultaneously. However, many viable, synergistic examples of stacking (multiple uses of storage) have been identified (FCH JU, 2015): for example, transmission and distribution grid investment deferral could be combined with arbitrage and reserve provision provided these are all physically viable simultaneously. High values of energy storage have been identified by using a whole system cost minimisation approach, balancing and aggregating benefits across various sectors, including networks, generation capacity and system operation (Strbac *et al.*, 2012).

Marginal value of additional storage. The marginal value of energy storage decreases with increasing installed capacities. While high values can be achieved with small additional storage capacities, the marginal value may fall steeply as capacities are increased. This has been studied by adding increasing capacities of energy storage while fixing other parameters (for example DENA 2012). Areas with high shares of variable renewable generation have a large potential market for electricity storage, although the marginal value falls with increased installed capacities of storage (Tuohy and O'Malley, 2011; Kiviluoma *et al.*, 2015).

Value of storage depends on services provided. The value of an electricity storage plant (and its potential profitability) depends heavily on the services provided. For example, Denholm *et al.* (2013) found that using storage only for reserves was significantly more valuable than using it for energy arbitrage and for reducing the curtailment of renewable electricity generation, and that there was a small further increase in value when a combination of reserves and arbitrage was provided. In addition, the flexibility (for example cycling and ramping capabilities, and minimum generating/charging levels) of the storage plant has a large impact on its potential value and profitability (O'Dwyer & Flynn 2015).

Isolated systems and areas with weak interconnections. Islands, remote locations and areas with micro-grids face particular challenges in integrating large shares of variable renewable generation (Manz *et al.*, 2014). This is because isolated systems must maintain a balance between their supply and demand without the benefits of regional diversity and smoothing, which occur over large areas in interconnected systems. Electricity storage has already been quite widely used for balancing in isolated systems, which are typically smaller, less robust and more susceptible to frequency deviations in the event of a disturbance (a given outage on a larger system will represent a much smaller percentage of the overall load), and hence have greater reserve requirements. For example, an economic assessment of an electricity storage system providing peak shaving and reserve on two Spanish islands demonstrated large potential cost savings and estimated internal rates of return of 7.25–8% (Sigrist *et al.*, 2013). An assessment of electricity storage on the island of Crete found greenfield storage capacity to be economically interesting under present conditions, owing to the availability of curtailed energy and the high cost of fossil fuels displaced by the storage (FCH JU, 2015).

Competitiveness of storage. The competitiveness of storage when compared with alternative flexibility options depends not only on the costs of storage but also on the flexibility needs of the system, and on the costs and possibilities to exploit other flexibility options (Kivluoma, 2013; Cochran *et al.*, 2014; IEA, 2014; Kiviluoma *et al.*, 2015). For example, storage may find it difficult to compete with existing dispatchable generation, especially where hydro generation is available with large reservoirs.

Expected deployment. System studies typically estimate the efficient deployment of a resource by minimising total costs. For example, the NREL Renewable Electricity Futures Study (National Renewable Energy Laboratory, 2012) estimated deployment levels for energy storage in a range of future high renewable (80%) scenarios. All modelled scenarios resulted in large increases in the installed storage capacity (80–131 GW from a base of 20 GW), with particularly high levels of investment seen in the constrained flexibility scenario (reduced capacity values and increased reserve requirements for wind and PV, reduced flexibility from thermal plant, limited demand response). It is also possible to estimate the expected deployment of a resource, by modelling the optimisation behaviour of different agents operating under different market incentives that will act as a distortion over cost minimisation results. For example, in a German study, the consequences of household optimisation behaviour induced by the indirect financial incentive for in-house PV electricity consumption were analysed by combining a household optimisation model with an electricity optimisation model (Jägemann *et al.*, 2013). The results demonstrated potential cost savings of 10–18% for participating households at the expense other electricity consumers and the network operators, with the overall system cost increasing significantly.

4.3 Gaps and priorities for further research on electricity system modelling

Accurately valuing dedicated energy storage is a complex task. The EASAC working group has identified several gaps and priorities for further research on energy system modelling, based on discussions within the group and with the scientific community.

To accurately capture the value of energy storage (and other sources of flexibility), it is important to consider the entire electricity system because focusing on a smaller region can either underestimate or overestimate the requirements, depending on how cross-border power exchanges are modelled. However, large system models do not contain sufficient detail (time resolution, network detail) to accurately value dedicated storage in applications. Simplified modelling approaches can play an important role within large system models, for example representations of the network and the supply and demand sides, although appropriate levels of detail and careful calibration are required to ensure good estimations of the system challenges are still achieved. It is important that system models encompass all flexibility competitors, for example the integration of power and heat and other forms of demand response, in an exhaustive way, with competing sources of flexibility co-optimised.

Investments in dedicated storage may be highly driven by uncertainties about future events, for example price spreads in the wholesale electricity market (Fürsch *et al.*, 2014). How uncertainty impacts the value of storage in a system needs to be better understood. While advances have been made in modelling uncertainty through dynamic and stochastic programming, the usefulness of the models will depend on the quality of the large volumes of data required, and the creation of such data needs more focus. In addition, the various feedback effects between decentralised storage and the operation of the overall electricity system need to be better understood.

5 Policy options affecting future markets for electricity storage

The process of selecting the most appropriate future policy options for the EU electricity sector will be driven by the need to ensure efficient and stable power system operation at the lowest possible cost, while the fraction of variable renewable electricity continues to grow in response to a continuing drive to reduce carbon emissions. Against this background, the future deployment of electricity storage in the EU will be strongly influenced by future EU policies regarding (1) electricity market design (including structure of retail tariffs and regulation of system operators), (2) electricity system operation (regulations, directives and network codes) and (3) technology investments (including EU and EIB funding, and Member State incentives)

Electricity storage is already being connected to electricity grids around the world for several different reasons, but the full multi-purpose potential of grid-connected dedicated storage assets may not be being realised. To secure the best value for money from electricity storage, future EU energy policies should provide an electricity market framework in which dedicated electricity storage is given an even chance of success when competing with all other flexibility options, including flexible generation, curtailment, demand response, grid reinforcement/interconnections. However, to deliver equal opportunities for all competitors in the market is not a straightforward task for EU policy-makers/legislators and regulators because the business models of many of the existing stakeholders (including utilities, network operators, independent generating companies, and users) depend on the existing market design (framework of rules, subsidies and incentives), and there may therefore be a natural resistance to change.

An added challenge is that some future policy options for increasing flexibility fall into the regulated and some into the competitive parts of EU electricity markets. This is important because a combination of options would probably be the most cost-efficient way of meeting the growing need for flexibility; however, the system operators, who are required to operate exclusively in the regulated parts of the market, have unique access to information that is needed to determine the lowest cost options, which potentially allows them also to influence the working of some competitive parts of the market.

A special asset class for storage, suggested by the IEA as a possibility (IEA–RETD, 2016), would permit tailored rules to be applied to its ownership and operation. For example, a special asset class would allow specific network tariffs to be applied for energy flows into and out of storage systems, to reduce the ‘double counting’ and/or double payment that currently has a negative impact on the business case for using storage.

Last, but not least, dedicated storage, flexible generation and grid reinforcement/interconnections require substantial capital investments, while demand response and curtailment have relatively low/no capital investment costs, which gives them an advantage.

5.1 Electricity market design options

Market designs, which reflect the physics and the true costs of the systems involved, will deliver the best overall value for consumers. This is an important reason why the EU electricity market design should provide equal opportunities for all technologies, including storage, to compete in all Member States.

While the overall energy demand in the EU is scheduled to fall in response to improvements in energy efficiency, electricity demand is expected to increase its share of the overall energy demand over the coming years in response to further electrification of transport, buildings and services (EUREL, 2013). As a result, the three big sectors of the EU energy economy (electricity, heating/cooling and transport) will undoubtedly require more integrated market designs and legislative frameworks in the future, and these will open up many new opportunities for innovation, including the wider use of dedicated electricity (and heat) storage.

EU policy-makers have already recognised the need for improved flexibility management in electricity markets EC COM(2015) 339, and some countries have already begun to introduce new policies, legislation and implementation schemes into their electricity markets. The most important market design options are highlighted below.

1. *Allowing volatility of electricity market prices.* As its costs come down, electricity storage can be expected to increasingly improve the efficiency of power system operation by participating in energy markets, taking advantage of the increased price spreads and price volatility that will inevitably result from more significant penetrations of variable renewable generation (Wozabal *et al.*, 2015). To incentivise the participation of storage system operators (and other sources of flexibility), the market design should allow for both very low (even negative) and very high prices and should not apply artificial price floors or ceilings that distort the price signals related to flexibility needs.

2. *Capacity markets.* While in principle adequate capacity could be financed through volatile market prices, such an approach involves substantial risks for investors and potentially also for the security of electricity supplies. Capacity payments are already

being introduced in some EU Member States to ensure that there is adequate generation capacity, and new requirements for capacity adequacy are also being introduced. However, with the high levels of over-capacity currently in the EU (total installed capacity approximately 1 TW compared with peak demand of approximately 550 GW (ENTSOe, 2015)), it is difficult with their current costs for storage systems to compete in other than short-term balancing or peak-shaving markets. In addition, the capacity value of a storage plant is impacted by its energy-limited nature, which must be accounted for in contractual agreements for generation adequacy.

Nevertheless, storage systems can offer valuable generation capacity (the capacity value depending largely on the discharge duration (Sioshansi *et al.*, 2014), together with other advantages over conventional plant such as absorbing over-generation (and the corresponding reductions in curtailment), when flexible generators can only be taken off line.

If future markets are to reflect the physics and costs properly, then future market designs should provide for broad participation, with entry thresholds that allow participation of both centralised and distributed storage systems (where aggregators may play an increasing role) and, importantly, all competitors.

3. *Timing of energy markets.* More variable renewable electricity is often expected to imply more uncertainty on the supply side and to create challenges in terms of maintaining the supply/demand balance. However, because forecasts for variable renewable generation become more accurate as the time of the forecast gets closer to the time of dispatch, many mismatches can be traded out if the energy market has sufficiently short dispatch intervals and gate closure times, and energy storage is well suited to contribute to this.

4. *Bidding zones.*–The existing bidding zones may be adapted in the future (Commission Regulation (EU) 2015/1222) to facilitate more efficient use of both network and generation assets. Zones that are too small may exhibit reduced liquidity and issues of market power (influence) may occur. However, zones that are too large and do not reflect the physical constraints of the system may require higher levels of redispatch (that is, the system operator instructs generators to deviate from market quantities, which may not be feasible owing to congestion), which can lead to inefficiencies (ACER, 2014). If future market designs provide for bidding zones that will incentivise appropriate levels of generation investment in the correct areas, then electricity storage could contribute, depending on the local context.

5. *Ancillary services.* Increased penetrations of variable renewable generation can increase the operating reserve requirements. However, a well-designed energy market with shorter dispatch periods (from 1 hour towards 5–15 minutes) and short gate closure times (as close to real-time as possible) can reduce the need for some operating reserves. Today, ancillary services for frequency and voltage control are largely provided by thermal generators, which will increasingly be displaced by non-dispatchable renewable generators (at least at times of high wind/solar generation). Consequently, opportunities for new providers of ancillary services, including energy storage, may increase in future as ancillary services markets evolve. The ability of flexibility providers, including storage, to participate efficiently and cost-effectively in future ancillary services markets will always be limited by the relatively small market size. Moreover, it will also depend on the market design (for example, accepting lower bid sizes from small actors) and on the costs (capital and operating).

5.2 System operation options

While market design and system operations are closely linked, the working practices of the market actors, including the network operators, generators and electricity users, are also important. Systems operating practices are evolving to meet the challenges posed by the higher penetration of variable renewable electricity, which could have important impacts on the potential for deploying more electricity storage in the following ways.

1. *Curtailment.* At times of high variable renewable electricity generation compared with the demand, the price of electricity may drop to zero, or even negative values, either because of congestion on the grid or for other operational reasons. It then makes sense for some renewable generators to be curtailed, unless other flexibility options are economically more efficient, for example exporting the excess energy via interconnectors to neighbouring regions, using the excess energy (demand response) for other purposes (for example power-to-heat, or P2G), or storing the excess electricity in a dedicated electricity storage system. While storing electricity locally avoids having to transform the electricity over different grid voltage levels with its associated losses, balancing over larger areas is typically more efficient from a system point of view and reduces the need for storage (which also has associated losses).

   In some isolated systems, variable renewable generation may need to be curtailed by the system operators to avoid instability at a system level because a percentage of synchronous generation is required to maintain stable operations (O'Sullivan *et al.*, 2014). In wind-dominated systems, there can be long periods between high-wind-speed events, which might require curtailment; and these events may involve large amounts of energy, which make the economics of using dedicated storage to reduce the need for curtailment challenging. In contrast, in PV-dominated systems, the power generation cycles are more predictable and the challenge of using storage to reduce curtailment is less significant (Kiviluoma *et al.*, 2015).

Article 16 of the EU Renewable Energy Directive 2009 requires (subject to maintaining secure operation of the system) that renewable electricity be given guaranteed access together with either guaranteed access or priority dispatch. Therefore, until recently, renewable generators have only rarely been subjected to curtailment and, notably in Germany (EEG, 2014) and Ireland, remuneration for renewable electricity has been paid even when market prices have fallen below zero. However, as the market penetration of variable renewable electricity generators has increased, the requirement for priority dispatch has come under increased scrutiny (for example, if prices fall below zero for more than 6 hours in Germany, then EEG-subsidised systems are no longer paid while they are curtailed). If priority dispatch for variable renewable electricity generation is discontinued more widely after 2020, then, at times of low demand and/or excess renewable electricity supply, a mix of competing solutions to address periods with potentially high levels of curtailment can be expected, including electricity storage, export of power to other bidding zones or countries, power-to-heat, P2G or power to other uses.

2. *Congestion management.* Closer transmission system operator and distribution system operator coordination will be required in future to manage congestion jointly because energy will increasingly be found to flow in both directions (at transmission and distribution levels), which may require a coordinated approach to the use of storage. The addition of more distributed generation may also require revisions to existing approaches for congestion management, such as changes to the geographical limits of bidding zones, which may offer new opportunities for electricity storage to add value to system management.
3. *Demand response.* Demand response is a competitor of electricity storage for providing flexibility to the grid. As highlighted in the EU Energy Efficiency Directive, demand response can be used to reduce demand at critical moments (load shedding) and to time-shift demand to help with balancing the system (load shifting) and to provide capacity (Nolan *et al.*, 2017). Indeed, large industrial customers in many countries have been participating in electricity markets on this basis for years and providing flexibility as they react to price signals.

   Smaller (including domestic) consumers could in principle also contribute to balancing and providing reserve, for example by switching off or on heating or cooling systems that have inherent storage, such as buildings, cold rooms or heat pumps in response to price signals. However, this would require consumers to participate in a dispatchable load programme or to be charged using time-varying tariffs with more intelligent meters to manage the process. Initial studies in Germany (Dena, 2010) suggest that demand response by households has limited economic potential compared with that by industrial consumers, and would not be competitive with other flexibility options (Nolan and O'Malley, 2015). Nevertheless, the potential impacts on system operation of such household participation in electricity markets and how they should be set up, considering grid constraints, would appear to justify further investigation (Heinen *et al.*, 2016).

   A group of interested market actors is working together through the Smart Energy Demand Coalition (SEDC, 2015) to develop detailed plans for the implementation of demand response options across the EU. This work is expected to help system operators to manage the higher peak demands for electricity that will accompany the increasing electrification of heating/cooling and transport, as well as to achieve more favourable asset utilisation in the future.

5.3 Investment financing options

The current design of electricity markets in the EU was developed at a time when there was excess generating capacity, and most of the required infrastructure was in place. Since that time, binding targets, dedicated incentives and subsidies have been added (using EU directives) to provide investor confidence in renewable generation, and dedicated EU financing has been provided to promote investments in grid reinforcements/interconnections and potentially in electricity storage, for example through the Connecting Europe Facility (EC, 2016e).

If a framework with equal opportunities is to be provided for the future, in which all of these assets can compete fairly, then all of the relevant EU policies and financing schemes should include resilient governance aiming to maintain investor confidence and technology neutral provisions for all of the competing capital investment options that is, generation, grid reinforcement/interconnections, and dedicated storage, as follows.

1. *Generation financing*. To meet the 2030 EU targets for renewable energy consumption, it is currently expected that more than 45% of electricity will be generated by renewables, and that many of the existing thermal generators will be taken out of service either because they have reached the end of their useful lives or because they will no longer be making money/needed.

   By providing energy arbitrage and by participating in balancing markets, storage could reduce the amount of low carbon generation (renewables, nuclear, and carbon capture and storage) needed to meet carbon targets, and make important contributions to generation adequacy. Both of these activities could attract investment in storage systems during the next decade as existing generating plants are taken out of service.

   In the longer term, as the current high levels of over-capacity in EU power generation are reduced, an important new challenge for policy-makers will be to ensure that there is sufficient generating capacity when the wind is not blowing and the sun is not shining for an extended period of time, which could be several days. As discussed in Chapter 3, the challenge of delivering electricity during extended periods of very low variable renewable generation will have to be met largely by using thermal and or hydro generation – probably in combination with dedicated storage – because it will not be technically or economically feasible to build storage systems that are large enough to store the amount of energy needed to supply the EU for more than a few hours.

   Hydroelectric power plants with large reservoirs could help to meet the new challenge because they can be managed as flexible generators, delivering power to the grid when the demand is high, but operating with a reduced output when wind or solar generation is available. Examples of flexible hydro power generation, with reservoirs that are large enough to be managed in this way, are already in use in Norway, Sweden, Switzerland and Austria, and discussions are continuing in Germany about the conversion of some large hydroelectric power plants in other European countries to pumped storage systems so that they can also store excess renewable electricity during periods of over-supply (Sachverständigenrat für Umweltfragen, 2010).

   In summary, there is a need either for thermal and/or hydro generators that are idle for long periods but nevertheless kept ready for use when needed, and/or for thermal and/or hydro generators with low levels of utilisation that are used periodically at part load (possibly with reduced efficiency), but can be ramped up to produce high levels of power when needed. In both cases, the costs associated with maintenance, part-load operation and ramping, which represent a small part of the overall power system operational costs today, will be higher in the future, and will need to be financed.

2. *Grid reinforcement/interconnections financing.* Strengthening transmission line interconnections within and between European countries is being promoted across the EU with the aim of opening up EU electricity markets by facilitating the trading of electricity across national borders and between electricity market areas within large countries. Better interconnections can facilitate more efficient use of resources, lower prices for consumers, and less need for other flexibility options, including storage.

   Other flexibility options, including storage, can be used as temporary measures for investment deferral and for managing delays in the strengthening of the grid, while awaiting approvals from the local and regional communities involved. However, in the long-term, grid reinforcement measures and better interconnections will be strong competitors for the other flexibility options, so it makes sense for these to be promoted and part financed at EU level.

3. *Storage financing.* Electricity storage can be installed to provide a range of services on transmission and/or distribution grids, but it will always face potential competition in electricity markets from other options for adding flexibility to the grid. Short-term incentives, targets or demonstration programmes that promote the deployment of storage on electricity grids have been implemented in many regions globally (Moore & Shabani, 2016), although it is too early to assess the impact that these will have on the wide-scale deployment of energy storage on a long-term basis. To ensure that storage is deployed effectively, it should be allowed to compete for financing on a level playing field with the other options.

5.4 Self-consumption

1. *Batteries and aggregators.* Consumers are already installing battery storage with PV for self-consumption, and aggregators are looking to develop new businesses that will help these systems to compete in electricity markets (Deign, 2015). A market incentive programme in Germany has led to significant levels of investment (see Box 5.1), and a growing interest in this technology has also been seen internationally (AECOM, 2015). Standards, information and communications technology protocols, infrastructure, rules for prosumers and aggregators,

tariffs, regulations, codes, etc. will need to be developed and/or updated to manage larger numbers of such systems in the future.

2. *Investments.* Householders are investing in small battery storage systems for self-consumption largely in response to current tariff structures and PV support schemes, which distort the market to promote the use of renewable generation, but also because it gives them a feeling of ownership and pride as well as an opportunity to participate in the energy transition (Römer *et al.*, 2015). Electricity market design should not block such opportunities for consumers.

   Householders are accustomed to investing in depreciating assets but, to avoid slowing this useful flow of low-cost financing into the electricity sector, and to maximise the value to the distribution grid of the storage involved, it will be important to incentivise the battery owners to provide services to the grid, to reward them for doing so, and to permit the involvement of aggregators in their management.

3. *Future domestic energy tariffs.* As the penetration of variable renewable electricity increases, electricity supply costs in many countries, which have for a long time been strongly influenced by fuel costs (especially for gas- and coal-fired generation), are becoming increasingly dominated by investment costs (wind, solar and network infrastructure). The balance of tariffs can therefore be expected to shift towards higher network charges (per kilowatt) and lower energy charges (per kilowatt hour), together with more emphasis on varying charges over the day to help with the management of congestion and the balancing of supply and demand. More time-varying tariff structures may help to promote the use of demand response; however, a shift towards higher network charges and lower energy charges would make self-consumption (with or without battery storage) less attractive to individual householders, although it could result in a more fully demand-related sharing of the total electricity supply costs between all consumers and promote more efficient utilisation of assets through meaningful price signals. Nevertheless, while support schemes for renewable generation remain in place and consumers continue to be motivated by the concept of self-consumption, storage could still play a role at the consumer level in minimising consumer bills (Naumann *et al.*, 2015), despite not necessarily being efficient from a system perspective. In addition, with revised operational strategies by system operators, distributed storage could still play a role in the future management of grid congestion.

Box 5.1 German experience with combined PV-battery storage systems

The German Federal Government and the state-owned Kreditanstalt für Wiederaufbau banking group issued a market incentive programme for PV-battery systems that came into effect on 1 May 2013. The programme aimed for an accelerated market introduction of PV-battery systems that increase self-consumption and provide grid relief at the same time. The funding was intended to stimulate the market, thus promoting technology development, and to reduce retail prices for small, dedicated battery systems in the long term (Kairies *et al.*, 2015). This funding scheme was updated in March 2016.

The speichermonitoring.de programme, which monitors this scheme, estimated that 40,000 German households were using PV-battery storage systems in 2016, with battery system prices of around €1000–2000 per kilowatt hour (mean battery size is 6.25 kWh).

A particularly interesting feature of the German funding scheme is its power cap: that is, the requirement that peak power exported to the grid should be no more than 50% of the peak PV power installed. This implies grid relief for the low-voltage distribution grids where most of the small-scale PV systems are located, and it opens up the possibility of installing more renewable energy systems in one grid segment without a time demanding grid extension.

The reasons why households make such investments are still being studied by researchers, but probably include a combination of subsidies/incentives, high electricity tariffs and self-sufficiency objectives. The ‘early adopter’ German householders involved have indicated that, in addition to their expectation of ever rising electricity prices, they are keen to support the German ‘Energiewende’ and have an interest in the technology itself.

If the standing charges (network costs) component of household electricity prices increases in the future and the energy component decreases, then self-consumption will become less economically attractive. However, if the prices of PV-battery systems continue to fall and public commitment to delivering an energy transition is maintained, then the markets for PV-battery systems could continue.

A recent survey of 339 households in Germany showed that PV-adopters have a higher intention to purchase battery storage systems than non-PV-adopters, and that social norms, a desire for independence and concerns about local security of supply influence the decision to invest in storage, but concerns about the general security of energy supply do not influence that decision (Römer *et al.*, 2015).

Another study of participants in the German incentive program for PV-battery systems (Kairies *et al.*, 2015) showed that strict monetary considerations were of minor importance to those private investors who had already invested in a PV system. They ‘reacted’ to the incentive programme for storage, and wanted to ‘do some good’ for Germany and the ‘Energiewende’.

6 Conclusions and advice for policy-makers

The conclusions and policy advice, which are presented below, have been compiled by EASAC, on the basis of the peer-reviewed information and independent analyses that have been presented in this report.

What is the value of dedicated storage?

1. **The value of dedicated storage on an electricity grid is system dependent**. The roles and opportunities for electricity storage and its competitors grow as the electricity systems grow, in particular as the penetrations of variable renewable generation increase. The same storage technology can offer several different services to the grid, and have different values in different situations. The business case for investing in storage becomes more attractive when one specific storage system can viably compete in more than one role/market at the same location (multiple use with value stacking).

2. **Storage is widely acknowledged today as an expensive option, but its costs are falling and its value is improving.** There are many conflicting claims and projections for current and future costs of the different storage technologies, and many ongoing research projects aiming at cost reductions. Among the different storage technologies, it is clear that batteries have the highest cost reduction potential and their costs are falling fast, partly as a result of the economies of scale that accompany their growing use, especially in transport applications. In contrast, the costs of other storage technologies are coming down more slowly but, for future large-scale applications, PHS in particular may offer good value for money in suitable locations.

3. **Storage adds value to electricity grids by contributing to the growing demand for flexibility (including congestion management), which is resulting from increasing levels of variable renewable generation (notably wind and PV) on electricity grids.** However, the demand for flexibility will be met in future by combinations of five competing options**,** namely flexible generation, curtailment, grid reinforcement/interconnections, demand response and storage. Flexible generation has been a major source of flexibility historically, but as capacity factors for peaking plants fall, investments become less favourable (particularly in the absence of capacity markets). Where they are feasible, curtailment, grid reinforcements/interconnections and demand response are typically cheaper than dedicated storage, but (a) the scope for *curtailment* is limited, the market is not yet ready in many parts of the EU for power-to-heat, and P2G is not yet commercially available, (b) it can take many years to build new grid reinforcements/*interconnections* because of public resistance and, (c) in many areas, systems may not yet be in place to manage dispatchable load programmes and end-use constraints may limit the potential for *demand response*. Consequently, it is reasonable to expect a growing penetration of dedicated electricity storage in future markets for flexibility on the grid.

4. **Storage adds value to electricity grids by contributing to balancing, reserves, network capacity, and generation adequacy.** PHS has been used for many years to provide balancing, and other storage technologies could contribute similarly to balancing and, in addition, to other key components of EU electricity markets in future. The use of storage to provide peaking capacity as well as reserves, permits the most cost-effective (high merit order) generators to operate with higher utilisation levels, thereby increasing their efficiency and potentially leading to lower electricity prices for consumers.

5. **Battery storage systems are valued by consumers, who are installing them increasingly at household level together with PV systems for self-consumption (prosumers).** This growing trend, which is being driven largely by consumer preferences as well as by incentives/tariff structures, falling PV and battery prices, and technology push by suppliers can bring financial benefits to PV and storage system owners, but may add to the costs of other electricity consumers and bring new management challenges for distribution system operators. It is attracting a new source of investment capital (householders) in distributed storage systems, but is an emerging challenge from an overall system perspective.

6. **Storage is particularly valuable in isolated systems.** In islands, remote locations and micro-grids, storage is needed to balance supply and demand because isolated systems cannot benefit from the regional diversity and smoothing that takes place across large interconnected systems, such as those in continental Europe. Some of the challenges faced by small isolated systems are also faced by relatively large but isolated systems, and in areas of the EU with poor interconnections.

What are the limits of storage?

7. **Storage will not substantially reduce EU needs for back-up generating capacity** in the short to medium term. Storage has traditionally been used

to smooth out peaks in demand, and it can similarly be used to smooth out peaks in supply. However, where over-capacity exists, it is difficult to justify significant additional investments in storage. As new capacity is required, storage can play a valuable role in contributing to generation adequacy and reducing system operating costs. However, none of the dedicated storage systems, which are commercially available for grid applications in 2016, is typically able to deliver its nominal power for more than about 10 hours, so they could not fill the gap when there is little or no supply from wind and solar generation during periods of several days with low wind speeds and limited sunshine. As a result, it seems likely that the most cost-effective solutions for providing generation adequacy in the coming decades will involve combinations of hydro and thermal generators along with dedicated storage.

8. **New technologies are not yet ready to deliver competitive seasonal storage of electricity for the grid.** Seasonal storage of grid electricity will not be needed until much higher levels of variable renewable generation are on line than is the case today. Nevertheless, several P2G options are being studied with the initial aim of producing synthetic gas for transport and industry, and these could be used within a few years to avoid curtailment of variable renewable generation. In contrast, the costs of P2G2P systems are far too high and their round-trip efficiencies too low to be deployed commercially for seasonal grid electricity storage applications within the foreseeable future, but they could perhaps be deployed within the 2050 timeframe.

What should be done to ensure that storage is used effectively?

9. **Electricity market design should deliver price signals (locational and temporal) that will encourage investments in the most cost-efficient flexibility options on both transmission and distribution grids.**

    (a) A redefinition of bidding zones (reflecting the physical constraints of the system) would help to deliver a cost-efficient mix of flexibility options and to avoid unnecessarily expensive systems being built.

    (b) Increasingly important for investors will be transparency about plans and rules for the future management of flexibility, because the marginal value of providing additional flexibility decreases as more is deployed on the grid. Particularly important for independent investors will be the planned split between (i) flexibility management within the regulated market by the network operators using interconnectors, international agreements, and possibly storage and (ii) flexibility management within competitive markets by means of flexible generation, demand response, and storage.

    (c) Authorities in several parts of the world have put in place short-term incentives, targets or demonstration programmes to promote the deployment of storage on electricity grids. However, it is too early to assess the extent to which these will lead to the large-scale deployment of cost-effective mixes of flexibility options on a long-term basis.

10. **Electricity market design should address the emerging challenge of more PV plus battery systems being installed by householders on distribution grids.** Most existing tariff structures focus largely on energy used (costs per kilowatt hour) and therefore produce a lack of price signals or in some cases counter-productive price signals regarding network costs (costs per kilowatt). While consumer wishes for self-production should be respected, it will be important that the costs of grid infrastructure be shared fairly across all users, and that any additional costs, which result from new clusters of PV systems being added to the grid, should also be attributed transparently to those who create them. Similarly, any benefits to distribution system management, which result from the use of (aggregated) household storage systems, should be fairly shared between those who provide them. Time-varying tariff structures with more intelligent metering are expected to contribute to the management of these issues.

11. **Electricity market design should be technology neutral, which means that it should not create barriers to the deployment of potentially valuable systems and technologies (including storage).**

    (a) Provision should be made to define and accommodate the specific features of all system assets and technologies for providing flexibility to the grid (including storage), so that they are not excluded or discouraged without good reasons. For example, without objective justifications, minimum bid sizes, lack of provision for aggregator involvement, and double payments for use of grid infrastructure (payment when energy comes into and out of storage) currently limit the participation of storage in some markets.

(b) Independent flexibility providers, such as storage system owners or aggregators of many small storage systems, should be allowed to participate in multiple markets provided it is physically possible to provide the multiple services simultaneously. In addition, independent owners of storage systems should be allowed to use them for regulated functions when contracted by system operators, but also free to use the same systems in competitive markets at other times. This would improve the business case for providing flexibility (for example by using dedicated storage) and improve the management of regulated networks at the same time.

(c) Public support at EU level for investments in systems to provide flexibility to the grid (for example via the Connecting Europe Facility or the European Investment Bank) should continue to give equal treatment to potential investments in all options for providing flexibility, including dedicated electricity storage.

12. **Policy for science.** More research and development is warranted with a focus on the following issues.

    (a) Continuing to reduce costs, for those dedicated storage technologies with significant potential for cost reductions, as well as pursuing continued technological advances for those storage systems. Key storage characteristics are application specific and those for dedicated grid-connected (stationary) applications are not necessarily well matched to those used for transportation (for example energy density and cycle life requirements can differ significantly).

    (b) Studies and analysis (including modelling) of transmission and distribution systems and markets, including socio-economic monitoring of demonstrations and innovation programmes, and of prosumer markets, as the market design evolves to meet increases in the demand for flexibility and as storage costs fall and its deployment increases.

Abbreviations

ACER	Agency for the Cooperation of Energy Regulators
BEV	Battery electric vehicle
CAES	Compressed air energy storage
DOE	US Department of Energy
EASAC	European Academies' Science Advisory Council
EASE	European Association for Storage of Energy
EEG	German Renewable Energy Act
EERA	European Energy Research Alliance
ENTSOe	European Network of Transmission System Operators for Electricity
EC	European Commission
Energiewende	Energy transition
EU	European Union
IEA	International Energy Agency
IEA–RETD	International Energy Agency Renewable Energy Technology Deployment
IRENA	International Renewable Energy Agency
JRC	Joint Research Centre of the European Commission
Li-ion	Lithium ion
NaS	Sodium sulphur
P2G	Power-to-gas
P2G2P	Power-to-gas-to-Power
PCI	Project of Common Interest
PHS	Pumped Hydroelectric Storage
PV	Photovoltaics
SEDC	Smart Energy Demand Coalition
TRL	Technology Readiness Level

Annex 1 Technology readiness levels (EU Horizon 2020 programme)

TRL 1: basic principles observed
TRL 2: technology concept formulated
TRL 3: experimental proof of concept
TRL 4: technology validated in laboratory
TRL 5: technology validated in relevant environment
TRL 6: technology demonstrated in relevant environment
TRL 7: system prototype demonstration in operational environment
TRL 8: system complete and qualified
TRL 9: actual system proved in operational environment

Annex 2 Peer reviewers

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Annex 3 Working group composition and timetable

The report was prepared in consultation with a working group of experts nominated by member academies of EASAC, and with valuable inputs from invited experts who gave presentations at project meetings and workshops (see details below).

Chairperson

Mark O'Malley, University College Dublin, Ireland

Working group members

Michael Ornetzeder, Institute of Technology Assessment, Austria
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Göran Strbac, Imperial College London, UK
Juha Kiviluoma, VTT, Finland
Christoph Ritz, Swiss Academy of Sciences, Switzerland
Dr William Gillett, EASAC Energy Programme Director

The first working group meeting was hosted by Imperial College in London on 1 April 2015, with invited guests Paul Denholm (NREL) and Göran Strbac (Imperial College).

The second meeting was hosted on 25 June 2015 by the University of Cologne with invited guests Craig Carter (MIT), Andreas Zucker (European Commission JRC), Joachim Birtsch (EWI), Andreas Lemke (Trianel) and Jochen Schwill (Next Kraftwerke).

The third meeting was preceded by an open workshop hosted by the Royal Academies for Science and the Arts of Belgium on 14 October 2015 in Brussels with the following invited speakers: Manuel Sanchez Jimenez (European Commission DG Energy), Norela Constantinescu (ENTSOe), Patrick Clerens (EASE), Daniel Fraile (EWEA), Andreas Zucker (European Commission JRC), Pavla Mandatova (Eurelectric), and Michael Flynn (investor). Informal preparatory meetings for this workshop were held with EC officials working on electricity sector policies and with Frauke Thies (SEDC). The working group meeting on 15 October 2015 in Brussels was hosted by the EC's Joint Research Centre (JRC) and attended by invited guests Ulla Engelmann, Efstathios Peteves, Andreas Zucker and Dora Dudas from the JRC. EASAC energy steering panel members were also invited.

The fourth meeting was hosted by the Royal Irish Academy on 23/24 March 2016 in Dublin, preceded by an open workshop with invited speakers Jonathan O'Sullivan (EirGrid), Gerard Finneran (Glen Dimplex), John McCann (SEAI), Mark Byrne (Gaelectric), Orla Nic Suibhne (Údarás Na Gaeltachta), John Ward (REDT), Peter Duffy (Schwungrad), Julia Badeda (RWTH Aachen) and Gerard Vowles (Gaelectric).

Annex 4 Acknowledgements

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