Support to R&D Strategy for battery based energy storage

Costs and benefits for deployment scenarios of battery systems (D7)

- Final 30 March 2017 –

Support to R&D Strategy for battery based energy storage

Costs and benefits for deployment scenarios of battery systems (D7)

By: Kris Kessels, Bart Mantels, Charlotte Hussy, Marian Bons, Farid Comaty, Minke Goes, Frank Wiersma, Anirudh Kshemendranat, Cedric Christensen, Patrick Hochloff, Dominik Schledde

Date: 30 March 2017
Project number: POWNL16059
Reviewer: Michèle Koper

Summary

This report presents the results from the socio-economic analysis of the BATSTORM project, a service project initiated by the European Commission in order to support the selection of R&D topics to be funded on the topic of battery based energy storage.

Batteries can provide a range of valuable services to the energy system as a whole, but also to specific actors in the (future) energy system. This report presents a first sketch of the potential role of batteries to provide these different services. The size of every service and the accompanying market share for batteries for each of these services, will however depend very much on the specific characteristics of the energy system at hand (thus varying from country to country) and on the availability and cost of competing technologies relative to the cost of batteries in the future.

Although the installed battery capacity base is still limited in Europe and worldwide, there clearly has been a significant growth in recent years based on a set of drivers, including (but not limited to):

- Increasing integration of Variable Renewable Energy Sources (VRES);
- Growing need for electricity grid stability, reliability and resilience;
- Rising self-production and self-consumption of energy;
- Increasing energy access and end-use sector electrification;
- Favourable energy policy, market design or regulation.

In the future, these drivers are likely to persist and in some cases grow, while some new drivers may materialise. Furthermore, most battery systems deployed today are used for a single application and are very often underutilized. There is thus an opportunity to increase the utilization factor of batteries by offering multi-services, thereby creating additional value for both the battery owner and the energy system as a whole, certainly for batteries downstream in the energy system.

Battery costs, particularly Lithium-ion, have demonstrated a significant cost reduction over recent years. Based on technology development as well as increasing scale at which these technologies are applied, there is a good basis to expect continued cost reductions over the next decades. This provides a basis for growing installed capacity of batteries in these various applications.

On the other hand there are a range of competing technologies that can offer services similar to those of battery storage systems at competitive cost levels. The growth potential for battery storage systems will depend on their future cost competitiveness relative to the evolving cost level of these competing technologies.

The deployment of battery storage in the EU can bring positive impacts in the field of economics, environment and social dimension. Economic impacts are expected through additional employment, additional sales and an increase in market volume. In the field of environmental impacts, an overall reduction of the use of fossil energy is expected, resulting in greenhouse gas emissions savings. However progress in the field of reuse and especially recycling are still necessary to amplify the

environmental benefits related to battery storage. With respect to the social dimension, battery storage can reduce costs directly at household level. But especially at system level larger savings are expected (e.g. by reducing peak demand, reducing cost of ancillary services, energy cost reduction by displacing costly generators and reduction of required investments in infrastructure).

Regarding the EU industry position and potential, opinions are diverse. Most identify establishing Li-Ion cell production capacity in Europe as necessary for Europe to further play a role in the international competition along the whole value chain of batteries. Furthermore plant engineering, material production, recycling, system development and integration are identified as main opportunities.

Abbreviations

AA-CAES	Advanced Adiabatic Compressed Air Energy Storage
aFRR	automatic Frequency Restoration Reserve
APC	Active Power Control
BESS	Battery Energy Storage System
CAGR	Compound Annual Growth Rate
CHP	Combined Heat and Power
CSP	Concentrated Solar Power
Ctg	Cradle-to-gate
DNO	Distribution Network Operator
DoE	Department of Energy
DSBR	Demand Side Balancing Reserve
DSM	Demand Side Management
DSO	Distribution System Operator
EFR	Enhanced Frequency Response
ESVT	Energy Storage Valuation Tool
FCDM	Frequency Control by Demand Management
FCR	Frequency Containment Reserves
FFR	Firm Frequency Response
FRR	Frequency Restoration Reserve
GHG	Green House Gas
HFB	Hybrid Flow Batteries
HVDC	High Voltage Direct Current
ICE	Internal Combustion Engines
LCA	Life Cycle Asessment
LCNF	Low Carbon Networks Fund
LP	Linear Program
mFRR	manual Frequency Restoration Reserve
MILP	Mixed-Integer Linear Program
MMT	Million Metric Ton
PFC	Primary Frequency Control .
PV	photovoltaic
RES	Renewable Energy Sources
RFB	Redox Flow Batteries
RR	Replacement Reserves
SAIDI	System Average Interruption Duration Index
SBR	Supplemental Balancing Reserve
SFC	Secondary Frequency Control
T&D	Transmission and Distribution
TFC	Tertiary Frequency Control

TSO	Transmission System Operator
VRES	Variable Renewable Energy Sources
VRLA	Valve-Regulated Lead-Acid

Table of contents

1 Introduction

This deliverable reports on the results from the socio-economic analysis of the BATSTORM project, a service project initiated by the European Commission in order to support the selection of R&D topics to be funded on the topic of battery based energy storage. The BATSTORM road mapping process will be based on a number of battery energy storage system (BESS) related targets derived from different sources [BATSTORM D8]:

1. The high level targets of the 2030 climate and energy framework;
2. The EC communication 'Towards an Integrated SET plan' which defines ten derived actions to accelerate the energy system transformation and create jobs and growth [EC 2015a];
3. Issues papers linked to these 10 actions with more specific and quantified targets.

In particular, the EC has set targets for stationary batteries in its issues paper 7 [EC 2016a]; According to this paper, R&I should aim at "*developing and demonstrating technology, manufacturing processes, standards and systems, which have the potential of driving high-efficiency (>90%) battery based energy storage system cost below €150/kWh (for a 100kW reference system) and a lifetime of thousands of cycles by 2030 to enable them to play an important role in smart grids*".

The socio-economic analysis will feed into this road mapping process by identifying the roles that BESS can play in the overall electricity system and the contribution they can thereby make to the SET plan targets. Energy storage, including batteries, can support energy security and climate goals by providing valuable services to the energy system. They can in effect play a crucial role in energy system decarbonisation by: improving energy system resource use efficiency; helping to integrate higher levels of variable renewable energy resources (VRES) and end-use sector electrification; supporting greater production of energy where it is consumed; increasing energy access and improving electricity grid stability, flexibility, reliability and resilience [IEA 2014a].

Batteries could thus provide different valuable services to the benefit of the energy system as a whole, but also to specific actors in the (future) energy system. Within this draft deliverable, we will give a first indication on the potential role of batteries to provide these different services from a socio-economic point of view. The size of every service and the accompanying market share for batteries for each of these services, will however depend very much on the specific characteristics of the energy system at hand and on the availability of competing technologies. Within *section 2 Energy System Analysis*, the current status and potential future role of batteries in the energy system will be described; Afterwards specifics and differences between different (future) energy systems will be described based on country cases including the need for batteries. Next, *section 3 Promising business models for batteries* will focus on current innovative business models, as they might advance the battery market. As battery cost is an important barrier for the introduction of batteries, *section 4 Battery cost development* will provide an overview of projected costs for the main battery technologies available from different studies. Next, *section 5 Competitive assessment of technological options* will compare batteries with other flexibility options (on technical and economic parameters). Finally, *Section 6 Battery capacity development scenarios* will bring all the information of the previous steps together to give a first estimation of the expected battery market for the different identified applications. *Section 7 Socio-economic impact of batteries* provides an overview of the environmental, economic and social impacts expected from the deployment of battery storage in Europe. Finally, *conclusions* are drawn in *section 8*.

2 Energy system analysis

Within this section, the role of batteries in the European energy system is described. First the current status of storage and batteries in the energy system is sketched and some of the underlying factors and trends which drive the application of storage, including battery energy storage systems, in the energy system are described. As a next step a list of potential applications for batteries in the European energy system is drafted and the potential of different battery technologies for these applications is analysed. As the need for storage in an energy system – including BESS - depends very much on the characteristics of these systems which are very often country-dependent, a screening is finally provided of the energy system characteristics and the regulatory and market framework of different European countries in the context of battery application.

2.1 The role of batteries in the energy system

2.1.1 Current status of batteries in the energy system

Figure 1 shows the worldwide installed electricity storage capacity in the energy system (MW) based on the U.S. Department of Energy (DoE) Global Energy Storage Database [DoE 2016]. The database is an online portal that provides information about grid-connected energy storage projects and relevant energy storage policies. The information posted on the website is vetted through a third-party verification process. In May 2016, there were 49 energy storage technologies included divided into four categories: electro-chemical, electro-mechanical, pumped hydro storage, and thermal storage. The resource lists operational projects in 57 countries and currently lists 16 services/use cases. The figure shows that at least 150 GW of storage is currently installed in electricity grids worldwide. The picture clearly shows that pumped hydro is predominant with a capacity of 145 GW and from the remaining storage options, batteries are clearly prominent (about 1.2 GW).

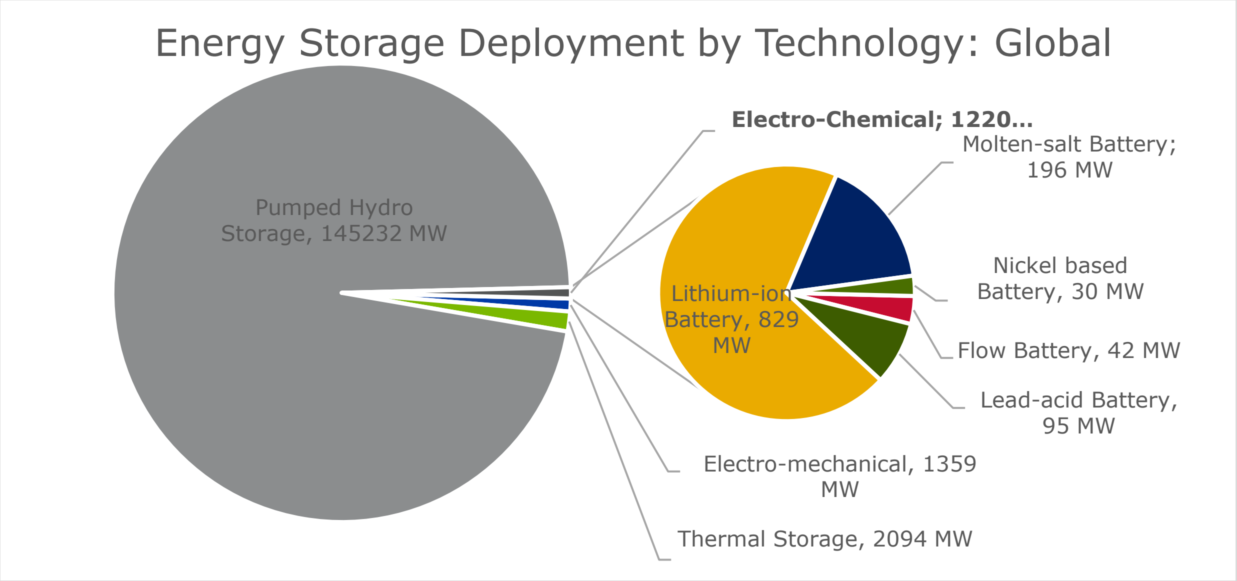


Figure 1: Global installed electric energy storage capacity [MW] / technology [DoE 2016][1]

Figure 2 shows the installed storage capacity for the European energy system. Currently at least 43 GW of storage is deployed in the European energy system, which represents about 30% of the global installed capacity. In terms of distribution, the same general trends can be seen. Batteries currently only represent about 0.4% of total European installed storage capacity, which is currently completely dominated by pumped hydro. Worldwide this number is slightly higher, i.e. 0.8%. Lithium-ion is the technology which is currently applied the most in the energy system in terms of capacity, followed by Molten-salt batteries.

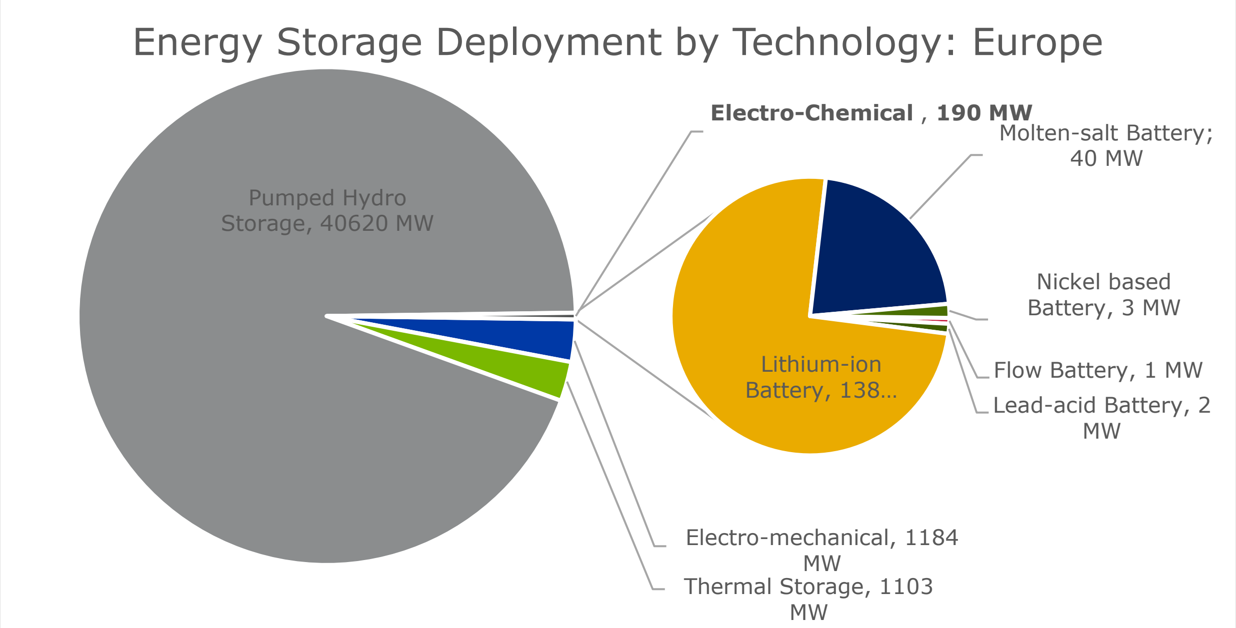


Figure 2: Electric energy storage capacity installed in Europe [MW] / technology [DoE 2016][1]

The figure below shows the ratio of battery storage installed in Europe compared to the global figures. Currently about one fifth of deployed batteries are installed in Europe.

---

[1] Battery systems at UPS systems are not included in this figure.

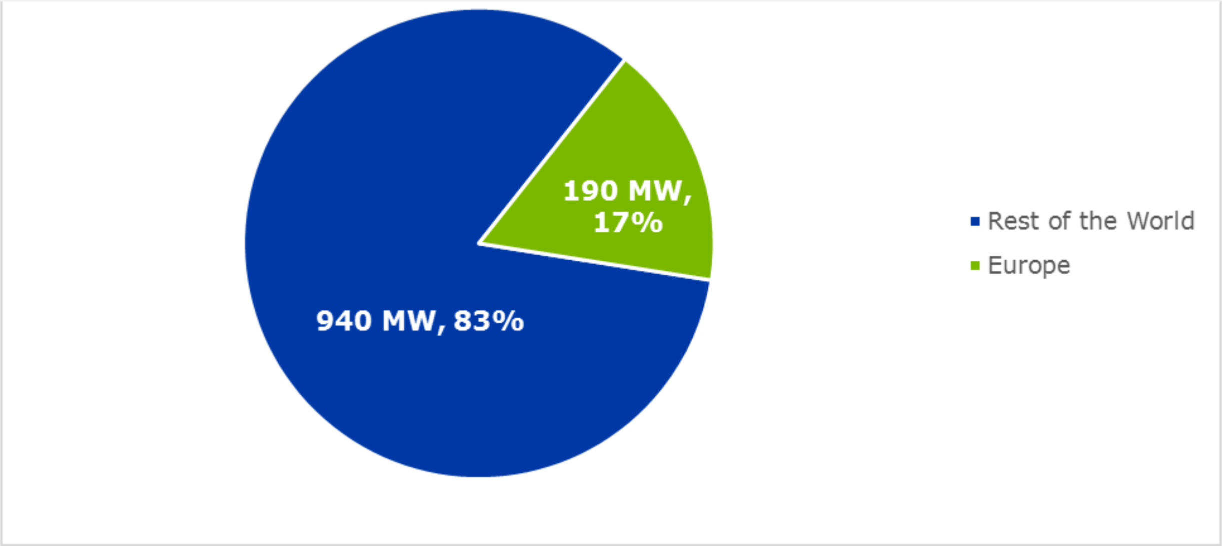


Figure 3: Total installed battery capacity in Europe compared to Total worldwide installed battery capacity [DoE 2016]

2.1.2 Drivers for battery development

Although the installed battery capacity base is still limited in Europe and worldwide, we do see an increasing trend, as shown in the figure below. In this section we will describe some of the underlying factors and trends which drive the application of storage, including battery energy storage systems.

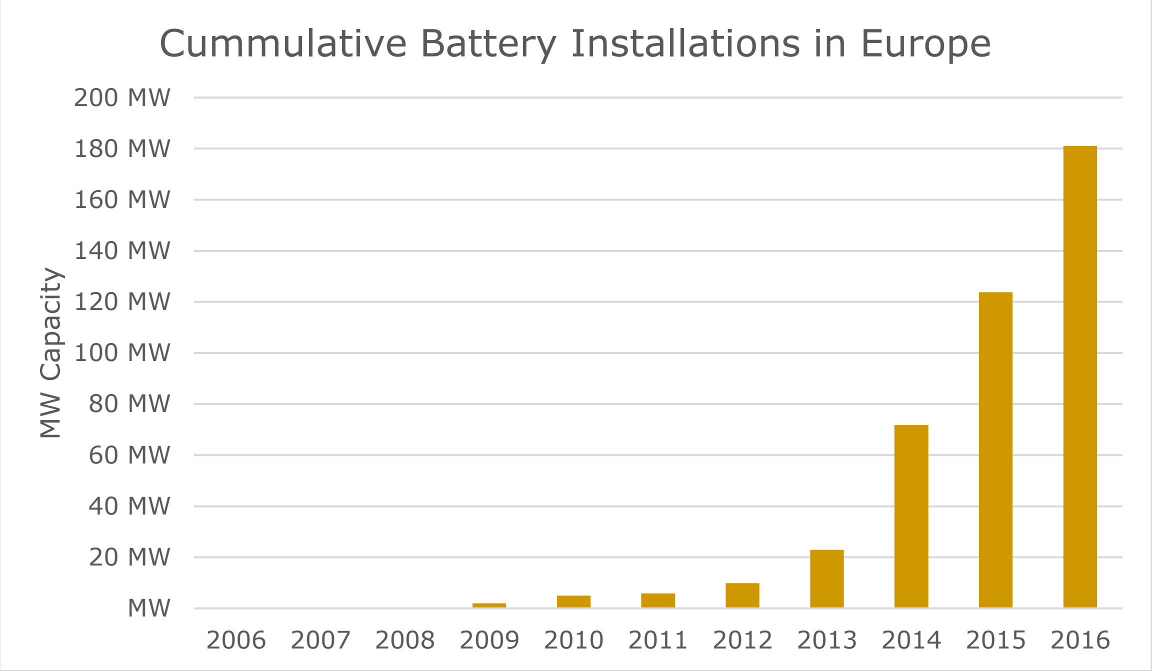


Figure 4: Cumulative battery storage capacity installed in Europe [MW] [DoE 2016]

The following list gives the most important drivers for battery storage. This is a non-exhaustive list. We will limit ourselves to drivers related to the energy system. Other aspects (e.g. battery cost) are omitted from this section as these will be dealt with in detail in section *4 Battery cost development*.

- **Increasing integration of Variable Renewable Energy Sources (VRES)**
  Solar PV and wind power have been expanding the last few years. The intermittent nature of both technologies calls for a redefinition of power system operation and planning and increases the need for flexibility in the energy system. Batteries can in this context be used to store excess renewable energy generated for later discharge. [IEA 2014a, IEA 2014b, INSIGHT_E 2014];
- **Growing need for electricity grid stability, reliability and resilience**
  Increasing amounts of fluctuating renewables place a greater emphasis on grid flexibility to ensure electricity supply stability, reliability and resilience. The technical term for describing the ability of an electricity system to resist changes in frequency is inertia. Low inertia can be expected in a small system such as an island with limited interconnection and few power plants. Storage may be essential to reliably integrate VRES in these systems. [IEA 2014a, IRENA 2015a];
- **Rising self-production and self-consumption of energy**
  More and more end users are installing decentralised generation (e.g. solar PV). These end-users are mostly driven by government support, concerns over electricity supply in areas with

a weak grid and/or economic trends. Local generation combined with battery storage could help to increase self-consumption or maximise savings or revenues (depending on the regulation) for these end-users. [IEA 2014a, INSIGHT_E 2014];

- **Increasing end-use sector electrification**
  Electricity demand is expected to increase in the coming years e.g. growing electricity demand for transport (EVs) and heat (electric heat pumps), thereby increasing the pressure on the energy system. Storage, including BESS (of course also inherently available in EVs), could play a role to store electricity during low demand periods and discharge during peak demand as well as alleviate congestion issues. [IEA 2014a, INSIGHT_E 2014];
- **Favourable energy policy, market design or regulation**
  Currently some markets and/or regulations stimulate the integration of battery energy storage systems in the energy system. In Germany, for example, the combination of decreasing feed-in tariffs for solar PV, support schemes for batteries and high electricity prices have created particularly attractive conditions for battery deployment at residential level combined with PV. In addition, as storage has been allowed to bid into the balancing market in Germany via pooling, the business case can be enhanced by aggregating these residential battery units into a large virtual storage to offer reserve services in the balancing market (see section 2.2.3). [IRENA 2015a];
- **Increasing energy access**
  In rural areas, consumers are often at a distance from the grid (and in some cases even with no access to the grid). In such areas, distribution grids represent a high cost per connection point, which can be even more pronounced when the grid becomes sensitive to disturbances and presents higher frequency of outages. As such, in such regions, there is an acute need to ensure electricity adequacy reserves for local off-grid situations, in order to face emergency situations or outages, which can be met with batteries. Moreover, in developing countries, small-scale BESS – charged by renewable energy – can help to deliver electricity to off-grid areas with no access to the public grid. [IEA 2014a, IEA 2014b, INSIGHT_E 2014].

The availability of these drivers within the energy system, is very location and country-specific. In section 2.2 we will therefore characterize the energy system for some selected countries.

2.1.3 Applications for batteries in the (future) energy system

The value of energy storage for the energy system lies in the application they can provide within the system. Many different studies have identified the applications batteries can provide to the energy system. The applications and their definition vary across these different studies. Based on several reports [IEA 2014a, IEA 2014b, RMI 2015, Sandia 2010, ISEA 2012], the classification of ancillary services according to the System Operations Guideline [EC 2016b], particularities of battery storage and our own internal analysis, we have drafted a list of potential applications for batteries in the European energy system in this section.

Different energy storage technologies can be mapped according to their characteristics. The figure below shows the ranges for power capacity and discharge duration for different energy storage technologies. The figure shows that batteries are well suited for applications which range from minutes to multiple hours and there are technologies available which cover power ranges from 1kW until about

100MW. Moreover they are typically very reliable and responsive with response times of seconds or even less.

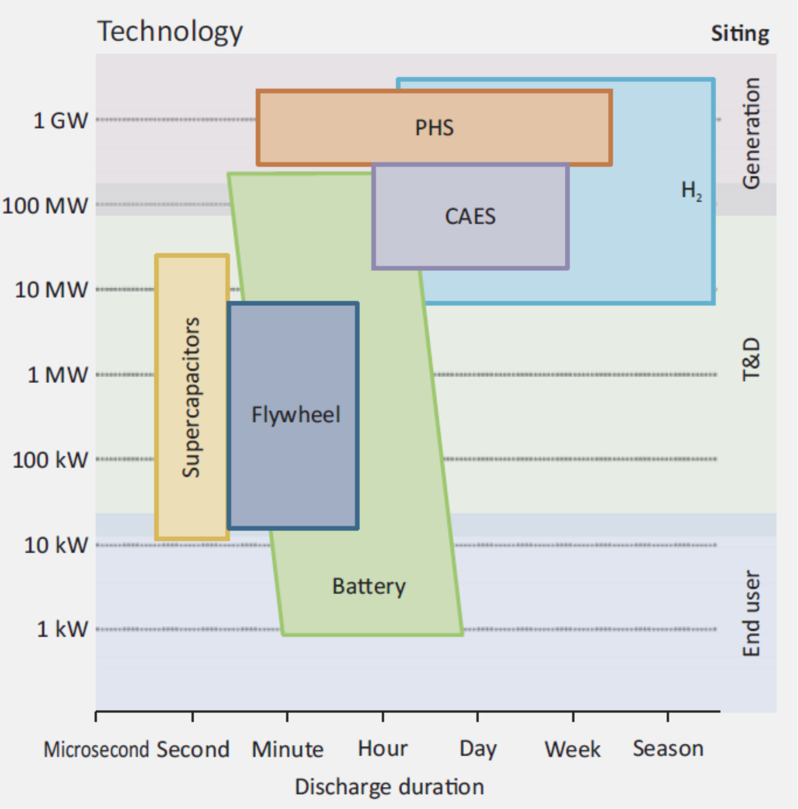


Figure 5: Energy storage technologies according to their characteristics (power capacity versus discharge duration) [IEA 2014b]

With this in mind and based on several sources (see above), we have assembled a list of potential applications for batteries within the European Energy system. These applications have been subdivided into four main categories, i.e. End-User Applications (Residential and Industrial), Ancillary Services, Transmission & Distribution (T&D) System Applications and Renewable Generation applications (RES applications). The figure below gives an overview of the different services which will be considered.

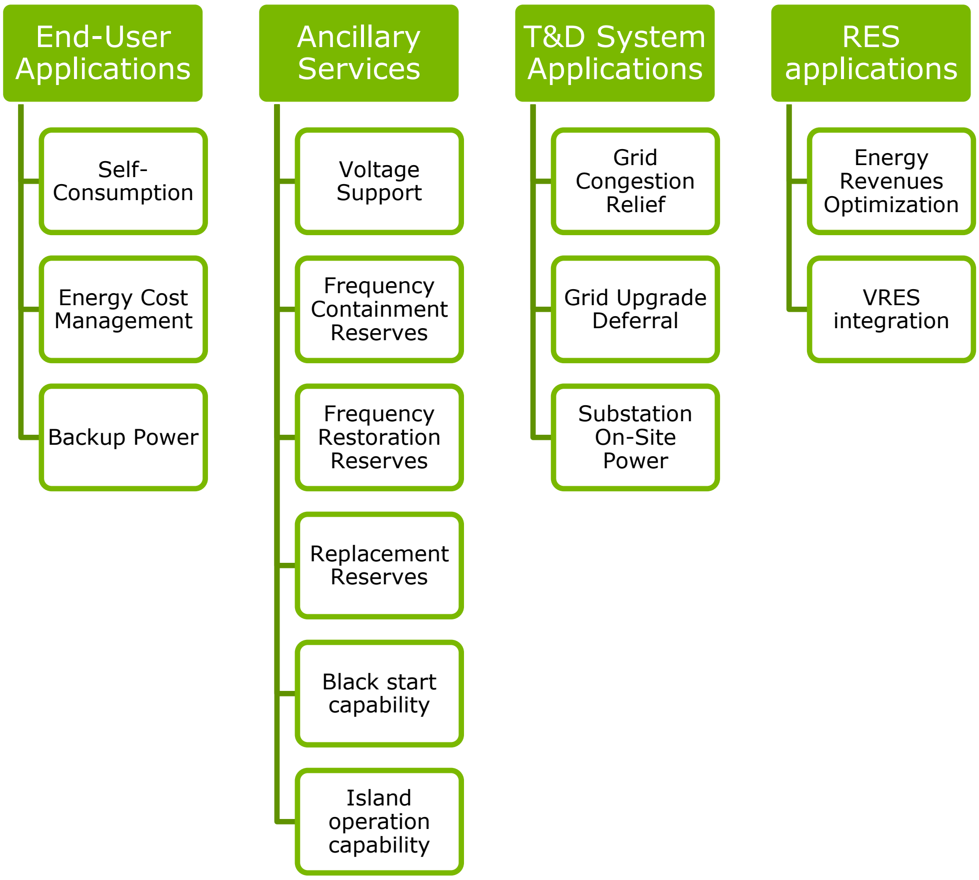


Figure 6: Potential applications for batteries in the (future) EU energy system

A full definition of these services can be found in the BATSTORM deliverable D5 Technical analysis of projects [BATSTORM D5]. The table below gives an overview of some of the most important characteristics of these services.

Table 1: Description and typical requirements of potential applications for batteries in the EU energy system. Adapted from [IEA 2014a, EC 2016b, ENTSO-E 2012, ENTSO-E 2013]

	Application	Description	Min Capacity[2] [MW]	Duration	Average installed capacity [3] [MWh]	Cycles	Response time
End-user applications	Self-Consumption	Using energy storage to maximize self-consumption from solar PV	0.005	Min to hours	0.005	< 1 per day	Minutes

---

[2] The figures given here give an indication of current minimum capacity levels for the different applications. Real values can however differ depending on the country. Moreover for certain applications and in certain countries, pooling of smaller units is allowed to reach applicable minimum capacities.

[3] These figures are based on the average installed battery capacity for each application taken from the U.S. Department of Energy (DoE) Global Energy Storage Database [DoE 2016].

	Application	Description	Min Capacity[2] [MW]	Duration	Average installed capacity [3] [MWh]	Cycles	Response time
	Energy Cost Management	Using energy storage to reduce the overall cost for electricity[4]	0.001	Hours	0.005	Multiple per day	< 15 min
	Backup Power	Providing backup power to end-user by means of energy storage in case of grid failure[5]	0.005	Min to hours	0.005	< 1 per year	Seconds
Ancillary services	Voltage Support	Injection or absorption of reactive power to maintain the voltages in the grid within a secure, stable range.	1-5	Seconds to minutes	1-2	Multiple per day	Millisecond to Second
	Frequency Containment Reserve	Operating reserves necessary for constant containment of frequency deviations from nominal value to maintain the power balance in the whole synchronously interconnected system.	1-5	Continuous or 30 min	1-2	Multiple per day (about 1 per day)	30 s
	Frequency Restoration Reserve	Operating reserves necessary to restore frequency to the nominal value and power balance to the scheduled value after sudden system imbalance occurrence.	1-5	15 min – 2 Hours	1-2	Multiple per day (about 1 per day)	15 min
	Replacement Reserves	Operating reserves used to restore the required level of operating reserves to be prepared for further system imbalance.	1-5	Hours	1-2	Multiple per day (about 1 per day)	15 min - multiple hours
	Black start capability	The ability to restart a grid following a blackout.	10	Hours	20	< 1 per year	< 1 hour
	Island operation capability	The ability to supply a grid area in isolation of the synchronous grid over extended periods of time.	0.1-1	Hours	0.2-2	< 1 per year	< 1 hour

---

[4] Depending on the overall cost structure (energy cost, distribution and transmission fee, other costs and charges), this can entail e.g. time-of-use management or lowering peaks at certain moments.

[5] This includes using energy storage to provide back-up power for a certain time span, to protect on site loads against short events which affect the power quality and to assure electric service reliability (e.g. transfer to on-site generation).

	Application	Description	Min Capacity[2] [MW]	Duration	Average installed capacity [3] [MWh]	Cycles	Response time
T&D System Applications	Grid Congestion Relief	Using energy storage to avoid grid congestion during peak periods.	1	Hours	1-2	Multiple per day	> 1 hour
	Grid Upgrade Deferral	Using energy storage during peak periods to defer grid upgrades.	1	Hours	1-2	Multiple per day	> 1 hour
	Substation On-Site Power	Provides power at substations in case of grid failure by means of energy storage.	1	Min to hours	1-2	< 1 per year	Seconds
Renewable generation Applications	Energy Revenues Optimization	Using energy storage in conjunction with VRES to optimize the income from VRES[6]	0.1-1	Min to hours	1-5	Multiple per day	< 15 min
	VRES integration	Using energy storage to optimise the output from VRES to increase supply quality and value.	0.1-1	Min to hours	1-5	Multiple per day	< 15 min

Battery storage can be deployed throughout the energy system. The applications that batteries can deliver within the energy system depend significantly on where the battery is deployed within the energy system. To get a better view on where batteries can provide which services, the following locations in the energy system need to be considered:

- Transmission grid;
- Distribution grid;
- Behind the meter
    - RES site
    - Customer site

The table below shows which applications can be delivered with batteries depending on their location within the energy system according to the categories of applications as introduced in Figure 6. The table clearly shows that the further downstream a battery is located within the electricity system, the more services it can offer to the system at large.

---

[6] This application includes complying with the nominated power schedule to avoid imbalance costs.

Table 2: Applications which can be delivered with batteries according to their location in the energy system

	Transmission grid	Distribution grid	Behind the meter[7]	
			RES site	Customer site
End-user applications				√
Ancillary services	√	√	√	√
T System Applications	√	√	√	√
D system Applications		√	√	√
Renewable generation applications			√	(√)[8]

When batteries are located behind-the-meter, they can offer most services and can even combine different services. If batteries are connected at distribution level, specific end-user and renewable generation applications can no longer be delivered. When moving to the transmission level, the same restrictions as for distribution-connected batteries are still applicable and in addition support to the distribution systems is no longer possible. Several demonstration activities such as the "Strombank" initiative in Germany demonstrate the technical viability for using batteries connected at distribution level for offering behind-the-meter applications [MVV 2016]. Several regulatory barriers however still remain that prevent the economic viability of using in-front-of-the-meter batteries for behind-the-meter applications.

Most systems deployed today are used for a single application and are very often underutilized. According to [RMI 2015] current batteries may sit unused anywhere between 50 and 95% of their useful life when they are only used for a single application. There is thus an opportunity to increase the utilization factor of batteries by offering multiple services, thereby creating additional value for both the battery owner and the energy system as a whole, certainly for batteries downstream in the energy system. Several barriers however still prohibit application stacking [BATSTORM D8]. On the other hand, batteries connected at a higher grid level may also have advantages compared to behind-the-meter batteries (e.g. economies of scale). A clear view on the optimal siting of batteries is currently lacking.

According to projections from the U.S. Energy Storage Monitor, by the end of the decade the capacity of behind the meter batteries installed each year in the U.S. will surpass centralized systems in front of the meter. The main underlying reasons are new tariff designs which incentivise self-consumption and more sophisticated market rules that allow distributed batteries to be pooled and allow them access to different applications. [GTM 2016]

There seems to be consensus, however, that batteries will be required at different locations within the energy system, depending on the local context and specific challenges to be addressed. This can for example be seen in the modelling results of the Massachusetts Energy Storage Initiative which evaluated the economic impact of incremental investments in energy storage in Massachusetts. The recommended share of 1766 MW additional storage was distributed across different locations depending on their specific use case and system benefits resulting in 58% located within the transmission and

---

[7] Within this table it is assumed that the customer or RES site is connected to the distribution system; If it would be connected to the transmission system, distribution system applications could of course not be delivered.

[8] For the application "Energy Revenues Optimization", the battery storage doesn't necessarily need to be placed at the RES site, but can also be placed on a customer site which belongs to the same trading portfolio. For the application "VRES integration", the battery storage does need to be located at the RES site.

distribution grid and 42% merchant and customer owned, of which at least 15.5% would be located behind the meter at residential and commercial/industrial sites. [DOER MASSCEC 2016]

Similarly, in October 2013, the California Public Utilities Commission adopted an energy storage target of 1,325 megawatts for the three investor owned utilities (Pacific Gas & Electric, Edison, and San Diego Gas & Electric) by 2020, with installations required no later than the end of 2024. The target calls for 200 MW of customer sited (behind the meter) energy storage. That's equal to 15% of the total target. However, thus far utilities in California have shown higher interest in procuring behind the meter energy storage to fulfil the target. For example, Southern California Edison purchased 261 MW of energy storage in 2014, of which 161 MW was behind the meter energy storage, already exceeding their "customer sited" target for the entire program. [SCE 2016]

2.1.4 Potential role of battery in the future energy system

As discussed in the previous section, there is a broad range of applications that operate at different time scales and have different requirements. Within this section, we will look into the potential role of different battery technologies to be applied for these applications. A view on competing technologies will be given in section 5.

Batteries are an attractive flexibility option for several reasons. Even if there are differences depending on the specific chemistry adopted (lead-acid, lithium-ion, etc.), they are generally pretty flexible and can be used both for power intensive and energy intensive applications. Moreover, they can be located in a place independently from its geographical characteristics and do not need a lot of space and time for installation. According to the Energy Perspectives 2014 by the International Energy Agency the true asset of BESS lies in their modularity, controllability and responsiveness as no other asset in the power sector can combine these characteristics [IEA 2014b]. There are different technologies for battery storage and technological innovations are ongoing.

Table 3 compares the main battery technology categories based on their overall characteristics. It should be noted, however, that battery performance not only differs per technology, but also per manufacturer and supplier. There are variations within each technology depending on the voltage level, the desired depth-of discharge, and load requirements [IRENA 2015a]. A more complete list of available battery technologies according to the same classification can be found in the BATSTORM deliverable D.5 Technical analysis of projects [BATSTORM D5]. The table below shows that the different battery technologies exhibit a wide variety of characteristics (e.g. density, discharge duration, response times,…), making batteries suitable for a large range of both power intensive and energy intensive applications. A distinction is made between: valve-regulated lead-acid (VRLA) batteries, flooded lead-acid batteries, lithium-ion batteries, nickel based batteries, metal-air batteries, molten-salt batteries, redox flow batteries and hybrid flow batteries.

Lead-acid batteries have traditionally been deployed in the energy system as they are a mature technology and have a relative cost advantage compared to other technologies. However, they suffer from technical drawbacks (i.e. low efficiency, limited cycle and calendar life and low power and energy density) compared to other battery technologies such as Lithium-ion for which interest is growing. In most cases, sealed valve-regulated lead-acid (VRLA) or flooded lead-acid batteries are used. The latter are cheaper, but require at least monthly maintenance to check and refill the battery with distilled water. Furthermore, they need to be operated in vented locations. [IRENA 2015a]

Lithium-ion batteries have a high power and energy density, which makes them very attractive for power sector applications requiring relatively short discharge and high power performance. Safety issues should however be considered and investment costs are rather high. [IRENA 2015a]

A number of batteries use molten salt as an electrolyte, and therefore have to operate under high temperatures. Molten slat batteries are already deployed in the energy system and are generally used for long periods of discharge lasting several hours. [IRENA 2015a]

Nickel based batteries are the only other type of battery to be demonstrated at grid-scale. They are more expensive than lead-acid batteries, but provide a higher energy density, longer cycle life and exhibit less frequent maintenance intervals. [Low Carbon Futures 2012]

Metal-air batteries have the potential to attain very high specific energy densities, but so far are still very expensive and are at the research and early demonstration phase. [Low Carbon Futures 2012]

A flow battery is a rechargeable battery where the energy is stored in one or more electroactive species dissolved into liquid electrolytes; They are classified into redox flow batteries (RFB) and hybrid flow batteries (HFB); In redox flow batteries, two liquid electrolytes containing dissolved metal ions as active masses are pumped to the opposite sides of the electrochemical cell; In a hybrid flow battery one of the active masses is internally stored within the electrochemical cell, whereas the other remains in the liquid electrolyte and is stored externally in a tank. Flow batteries are attractive for power system applications for several reasons, including power/energy independent sizing and long cycle and calendar life; They can typically be used for storing and discharging long durations of energy supply (typically between two and 10 hours). [IRENA 2015a, Piergiorgio, et al. 2014, Sukhvinder, et al. 2014]

Table 3: Characteristics of the main battery technologies

	Lead-Acid – VRLA	**Lead-Acid - Flooded**	**Lithium-Ion**	**Nickel based**	**Metal-Air**	**Molten-Salt**	**Redox-Flow**	**Hybrid Flow**
Optimal discharge duration	Few hours	Several hours	1 hour	Few hours	Few hours	Several hours	Several hours	Several hours
Power density	Low	Low	High	Medium	High	Low	Low	Low
Energy density	Low	Low	High	Medium	Very high	Low	Low	Low
Round trip efficiency	Low	Low	High	Low	Medium	Low	Low - Medium	Low - Medium
Investment cost[9]	Low	Very low	Medium - High	Medium	Very high	Medium	High Medium (potential)	High Medium (potential)
Operating cost	Low	Medium	Low	Low	Low	Medium	Medium	Medium
Cycle life	Medium	Low	High	Medium	Low / High (potential)	High	Very high	High
Calendar life	Medium	Low	High	Medium	Low / High (potential)	High	High	High
Reliability	High	High	High	High	High	Medium	Medium	Medium
Safety	High	High	Medium	High	Medium	Medium	High	High
Response time / ramp rate	Low	Very low	High	Medium	High	Medium	Low	Low
Standby loss / self-discharge	Medium	Medium	Low	High	Low	High	Medium	Medium
Recycling / environmental friendliness	Good	Good	Average	Average	Average	Good	Good	Average

---

[9] The qualitative assessment of the investment cost for the different technologies is based on the energy rating, i.e. batteries with the same energy content are assumed to compare the investment cost. The information in the table represents market perspective 2016.

In the future, probably different battery technologies will play a role and will be used, so there is no "one winner" [INSIGHT_E 2014]. Based on the characteristics of the main battery technologies - except for economic factors - the table below (Table 4) gives an indication of the technical capability of the main battery technologies to offer the services which have been identified in section 2.1.3. The table shows that the potential applications for different battery technologies can drastically vary. Moreover, if cost aspects are considered, the table might show another picture. Section 4 will therefore analyse current and projected battery costs for these different technologies, whereas section 5 will analyse the competing technologies. From Table 4 it is clear that depending on the characteristics of the different battery technologies, a certain battery technology might be less or more fit to offer a service. Overall though, a battery technology can be found which shows very good – to good prospects for each of the identified applications.

Table 4: Ability of different battery technologies to offer services for the (future) EU energy system

Application	**Important storage characteristics**	**Lead-Acid – VRLA**	**Lead-Acid - Flooded**	**Lithium-Ion**	**Nickel based**	**Metal-Air**	**Molten-Salt**	**Redox-Flow**	**Hybrid Flow**
Self-Consumption	Long discharge duration Long cycle life	🟢	🟠	●	🟢	●	●	🟢	🟢
Energy Cost Management	High efficiency	🟢	🟠	●	🟢	●	🟠	🟠	🟠
Backup Power	Reliability Low standby losses Long calendar life	●	●	●	🟠	🟢	🔴	🔴	🔴
Voltage Support	Fast response time	🟠	🔴	●	🟠	●	🟢	🟠	🟠
Frequency Containment Reserves	Reliability Fast response time Bi-directional	🟠	🔴	●	🟠	●	🟢	🟠	🟠
Frequency Restoration Reserve	Reliability	🟢	🟠	●	🟢	●	🟢	🟢	🟢
Replacement Reserves	Reliability Long discharge duration	🟢	🟠	🟢	🟢	🟢	●	●	●
Black start capability	Low standby losses Long calendar life	●	●	●	🟠	●	🔴	🔴	🔴
Island operation capability	Long discharge duration Long cycle life	●	●	●	🟠	●	🔴	🔴	🔴
Grid Congestion Relief	Long calendar life Low standby losses	🟢	🟠	🟢	🟢	🟢	🟠	🟠	🟠
Grid Upgrade Deferral	Mobility	🟠	🟠	🟢	🟢	●	🟠	🟠	🟠
Substation On-Site Power	Reliability Long calendar life Low standby losses	●	🟢	●	🟠	●	🔴	🔴	🔴
Energy Revenues Optimization	Long discharge duration Efficiency Low operating cost	🟢	🟠	●	🟢	●	🟠	🟠	🟠
VRES integration	Reliability Efficiency Fast response time	🟢	🟠	●	🟢	●	🟢	🟢	🟢

● High suitability / 🟢 Suitable / 🟠 Less suitable / 🔴 Not applicable

2.2 Energy system characterization: country analysis

As already stated, the need for storage in an energy system – including BESS - depends on the characteristics of these systems and is very often country-dependent. Figure 7 shows the distribution of installed battery capacity across Europe. The map clearly shows that some countries are frontrunners when it comes to battery deployment, i.e. Germany, Italy and the United Kingdom. The figure also shows that battery capacity seems to be applied the most in Western Europe while Eastern Europe lags behind. Battery deployment in the European energy system is anyway at a very early stage and in some countries favourable conditions have been created which explain the application of battery storage.

Respondents to our online survey indicated that Germany has the largest potential for using and advancing the state of the art in battery storage up to 2025 as they have the largest potential for RES self-consumption and a favourable policy. The UK was also mentioned by some participants as instabilities in the island's grid will drive demand for battery storage solutions. Different respondents pointed out that all southern Europe countries with high growth in PV installation have a potential for uptake in battery storage. In general, any country with a high percentage of RES penetration into the transmission and especially distribution system will be pressed to implement storage to provide services to cope with the local effects of distributed generation.

In this section we will therefore dive a bit deeper into the characteristics of the energy system of the three front-running countries: Germany, Italy and the United Kingdom. An additional advantage of covering these countries, is that they are geographically spread across Europe and therefore cover different climate zones. Moreover this allows to compare the particularities of an island (UK), a peninsula (Italy) and a very well connected mainland country (Germany). In addition we will also look into the characteristics of a fourth, smaller country, i.e. the Netherlands. As can be seen from the graph, the Netherlands has quite some battery capacity installed despite of its size, so we will look a bit deeper into the underlying reasons. This section will screen the energy system characteristics and the regulatory and market framework of these four countries, within the context of potential applications for BESS in the energy system as introduced in the previous section. Taking into account the drivers described in section 2.1.2, the following characteristics seem to be important in determining the potential role of batteries in an energy system:

- Evolution of the energy mix and demand;
- Grid and system challenges;
- Regulation and policy.

Figure 7: Distribution of battery technology applied in projects by European Countries [DoE 2016]

2.2.1 Evolution of the energy mix and demand

The power generation mix and the adequacy of the installed capacity, including future renewable energy projections, are relevant for identifying the need for flexibility options, including BESS, in the energy system. The European electricity system is made up of a variety of interconnected regional and national systems, each of which presents its particular generation mix. Even though there are common EU policy guidelines and key directives, the implementation at member state level differs from country to country, leading to a variety of foreseeable investment scenarios especially in view of renewable energy sources integration. On the other hand, market development is more and more guided by member state collaboration and EC initiatives.

The current situation (scenario 2014) [ENTSO-E 2015b] is compared in Figure 9 and Figure 10 (on the following page) to the estimation of potential future developments in new installed capacity for 2020 according to the TSOs (a mid-term 2020 ‘best estimate scenario’) of the selected countries. In addition, two envisioned scenarios for 2030 are covered, i.e. the 2030 vision of “National Green Transition” (2030 NGT) and the 2030 vision of “European Green Revolution” (2030 EGR) as developed by ENTSO-E in the framework of the ten year network development plan (TYNDP) 2016 [ENTSO-E 2015a]. Both scenarios assume that Europe is very well on track to realize the set objective of energy decarbonisation by 2050, but the scenarios defer according to their perspective of measures for decarbonisation of the energy system; This can be done in a strong European framework but not preventing Member States developing the options which are most appropriate to their circumstances (“European Green Revolution”), or secondly in a looser European framework effectively resulting in parallel national schemes (“National Green Transition”). “*Appendix A: Summary of elements of 2030 visions*” shows the main assumptions and the characteristics of the energy system within the two selected 2030 scenarios.

Figure 11 and Figure 12 (on the following pages) show respectively the highest and lowest load within the four selected countries and the demand projection within the different ENTSO-E scenarios.

From the graphs, it is clear that greater deployment of low carbon energy generation will be required in order to meet the 2020 EU mandated targets, as well as EU targets for renewable generation by 2030 and EU mandated carbon targets to be achieved on the way to 2050 within the three countries. Regarding demand projections, depending on the chosen scenario, demand may decrease (mainly due to energy efficiency) or increase (mainly due to the electrification of demand). If the EU is to meet the target of an 80% reduction in greenhouse gas emissions, on 1990 levels, by 2050, savings must also be made in transport and buildings (heat). Electrification of heat and transport could significantly reduce carbon emissions if the electricity comes from low-carbon sources, and electrification may become a dominant trend.

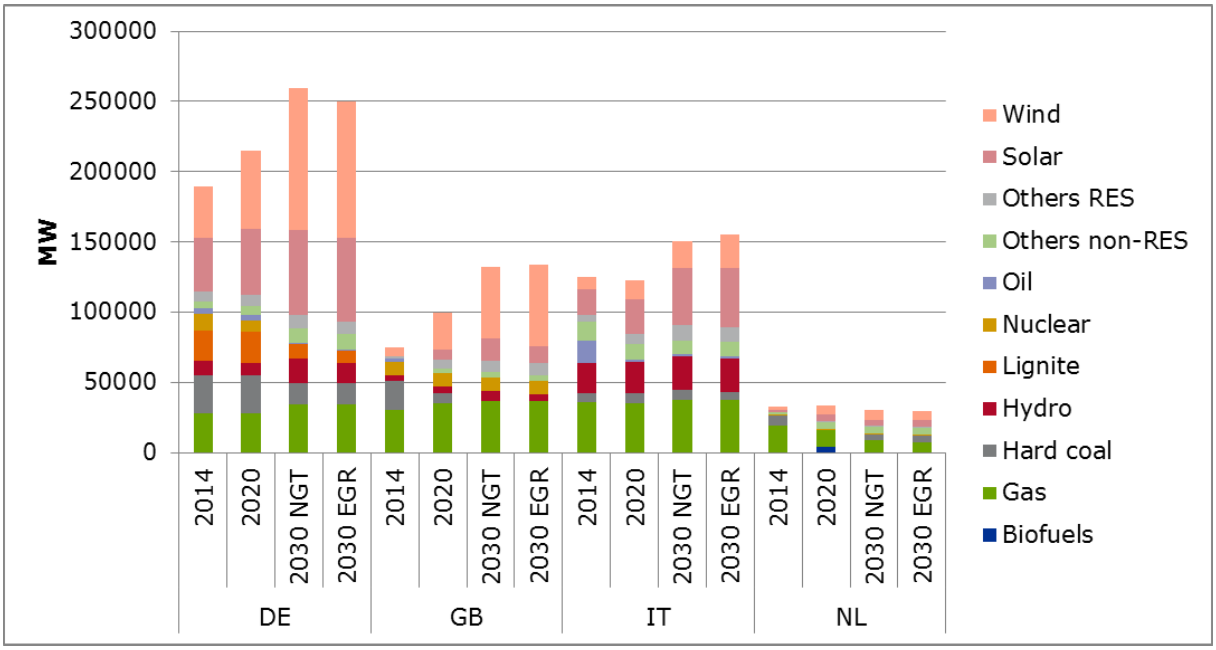


Figure 9: Current (2014), expected (2020) and envisioned (the 2030 vision of "National Green Transition" (2030 NGT) and the 2030 vision of "European Green Revolution" (2030 EGR)) generation mix (MW) of the target countries [ENTSO-E 2015a, ENTSO-E 2015b]

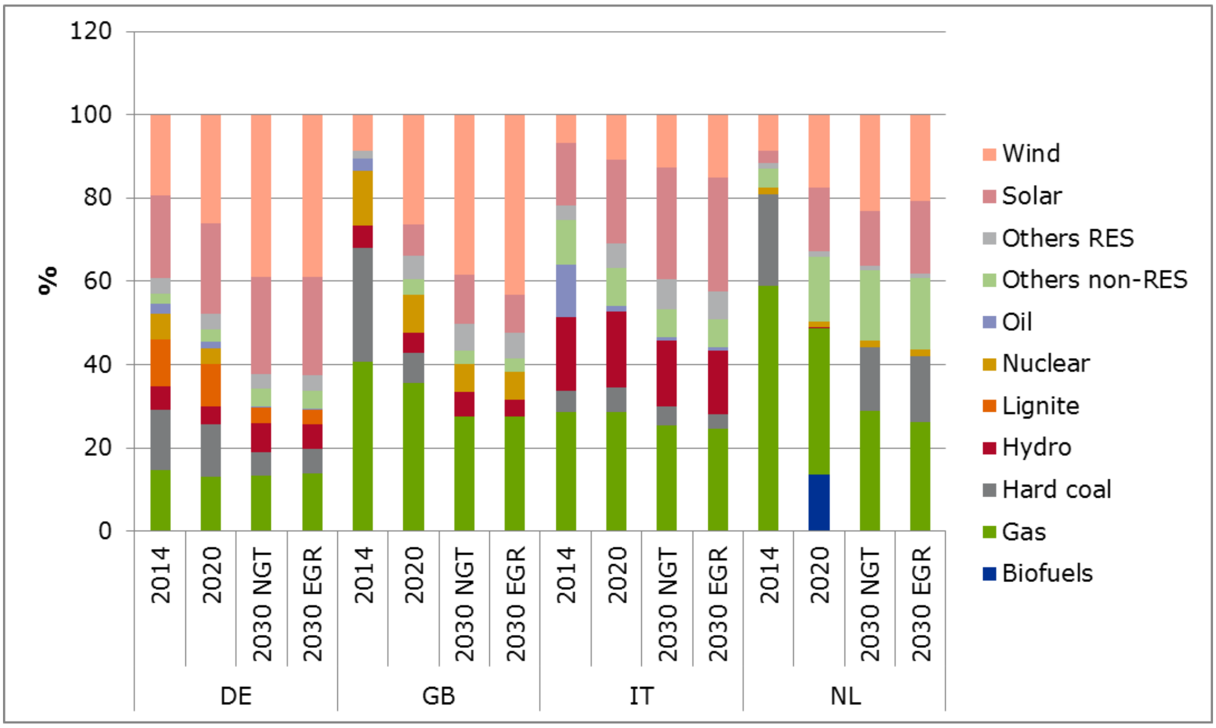


Figure 10: Current (2014), expected (2020) and envisioned (the 2030 vision of "National Green Transition" (2030 NGT) and the 2030 vision of "European Green Revolution" (2030 EGR)) share of each technology (%) in the generation mix of the target countries [ENTSO-E 2015a, ENTSO-E 2015b]

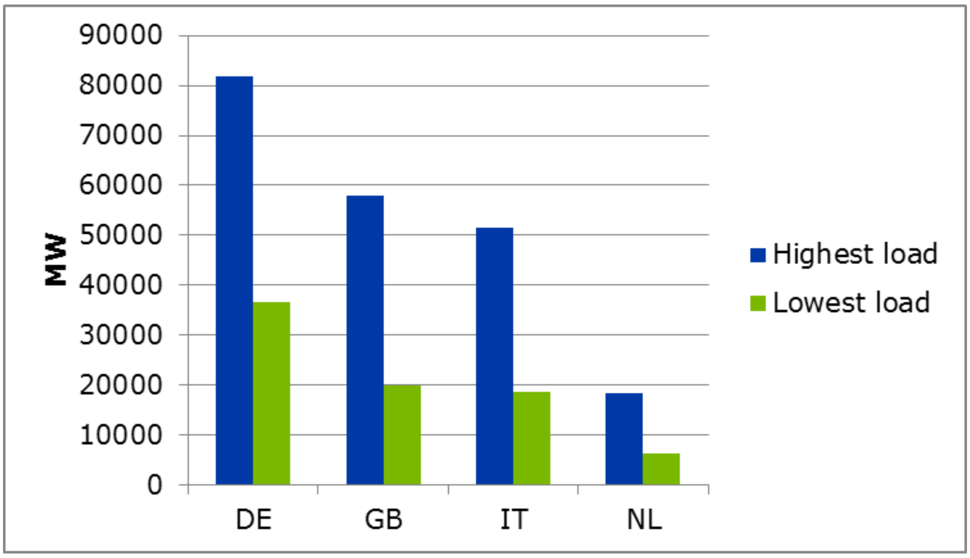


Figure 11: Highest and lowest hourly load values of the target countries 2014 (MW) [ENTSO-E 2015b]

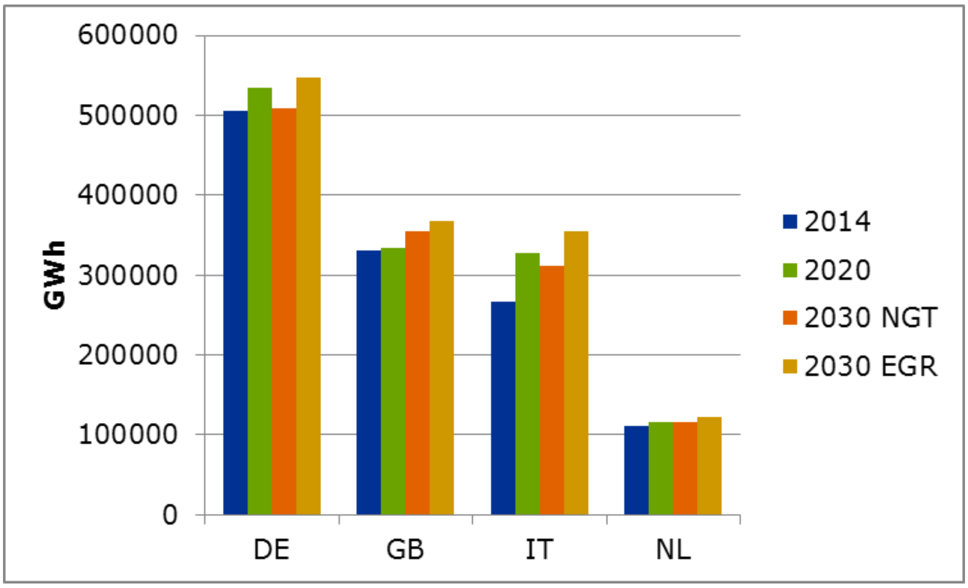


Figure 12: Current (2014), expected (2020) and envisioned (the 2030 vision of "National Green Transition" (2030 NGT) and the 2030 vision of "European Green Revolution" (2030 EGR)) electricity consumption in the target countries [ENTSO-E 2015a, ENTSO-E 2015b]

The **German** power system has the largest amount of installed capacity and is going through a deep transformation of its energy mix, mainly driven by a big support to renewable energy sources and the political decision to phase out all nuclear generating capacity in the next years (by 2022) after the Fukushima nuclear accident. Several German nuclear reactors were shut down after the Japanese nuclear meltdown in 2011 and the rest are to be phased out by 2022, while nuclear power had previously contributed about 25% of annual electricity production [IRENA 2015a], asking for a complete reorganization of the energy system.

The **Italian** power system is currently made up mostly of conventional thermal generation and a large share of renewable energy generation, most of it from solar. A large volume of conventional fast thermal capacity provides flexibility to the system but the increasing amount of VRES and the lower availability of thermal capacity urges for more flexibility.

The electricity generation mix in the **United Kingdom** is still very dependent on fossil fuels, but is increasingly incorporating RES, especially wind energy. According to Carbon trust and Imperial college [Carbon trust 2016] the following trends can be observed in generation and demand:

- The UK currently has, at operational level, 8.3GW of onshore wind capacity and 5.1GW of offshore capacity. If all projects under construction, consented or planning become operational, the total UK installed capacity of wind power would rise the coming years to 44.6 GW, evenly split between onshore and offshore wind;
- The growth of distributed generation has accelerated rapidly in the UK over the last few years owing to the introduction of feed-in tariffs, cost reductions of low carbon technologies, and changing attitudes towards self-generation. For example, installed solar PV capacity has seen a five-fold increase in the UK between 2011 and 2014;
- A number of UK coal-fired power stations have been closed. As a result, the current installed coal-fired capacity in the UK has already been reduced by 9GW since 2011 and will be further decreased;
- Unless flexibility is deployed within the energy system, the electrification of heat and transport is likely to result in significant increases in peak demand on the system that are disproportionately greater than the additional requirements for electricity to supply these sectors.

Currently, the power system in **the Netherlands** depends mainly on fossil fuels. In the last five years only a slight decrease in the share of fossil fuels has been realized. Because of the availability of natural gas in the Netherlands, a relatively high share of electricity is generated with natural gas, i.e. 50%. However, the share of natural gas has reduced the last years due to unfavourable market conditions. This led to an increase in the share of coal. Furthermore, the gas extraction in Groningen is under high social pressure due to earthquakes that are related to the gas extraction. In the coming years the share of natural gas is therefore expected to decrease further. The closure of five coal plants and the co-firing of biomass will also reduce the use of coal until 2020. After 2020, the use of coal is expected to stabilize. The share of renewable energy sources for electricity production has remained quite steady around 11% the last five years. This is a result of the simultaneous increase in installed capacity of wind energy and decrease in the use of biomass for the generation of electric energy. From 2017 onwards the share of renewable energy sources is expected to grow significantly under the influence of renewable energy subsidies (SDE+)[10], regulation of renewable energy in transport, energy performance standards for buildings, and tax measures. In 2030 almost half of the domestic electricity generation could be renewable (mainly from wind power and PV). However, there is strong uncertainty with regards to the increase of renewable energy due to a missing long-term political perspective. [ECN 2015, CBS 2016]

2.2.2 Grid and system challenges

Germany has a highly interconnected transmission grid [IRENA 2015a]. However, different factors such as geographic mismatch of power supply and demand have led to significant balancing issues from the northern suppliers and southern demand centres in the past years [IEA 2014a]. This problem was aggravated by local grid imbalances resulting from a sharp increase in the supply of wind energy in the north of Germany and a lack of energy supply in the south due to inadequate capacity on transmission lines. The improved integration of the European grid allowing for electricity imports and exports, has enabled Germany to overcome these balancing issues, but is causing issues in Eastern Europe energy systems. At present levels of about 30% renewable energy penetration (mainly wind and solar), the system has faced very few reliability issues. However, as wind and solar power increase, and fossil fuel plants go offline, battery storage may become an important option for both short and long-term supply fluctuations. This has prompted demonstration projects and research funding for battery storage implementation [IRENA 2015a]. Moving forward, the main challenge facing the German electric power system could be the local and temporal balancing of electricity supply and demand. While spatial imbalances can be managed or diminished by grid expansion, trans-regional temporal imbalances must be solved by other means according to the International Energy Agency [IEA 2014a].

According to Terna [Terna 2016], the **Italian energy system** has been and will increasingly be in need of flexible sources, among which BESS, to ensure system adequacy and reliability. On the one hand the economic crisis has led to the loss of many big consumers (i.e. national demand decreased 7% from 340 TWh to 318 TWh). On the other hand, an aggressive policy of incentives promoting renewable energy sources has led to fast and massive growth of RES. This all happened over a very short time period, so that time to fortify and develop the grid to support these new developments was lacking. The following effects can be observed [Terna 2016]:

- Rise in congestion-related RES curtailments (i.e. in 2010 500 GWh was lost);
- Loss of available frequency reserves due to the fact that traditional power plants are running at minimum load;
- Consequently, there has been a rise in demand for frequency reserve;
- And a loss of inertia in smaller systems (i.e. Sicily and Sardinia).

These effects have led to a strong focus on the optimization of the integration of RES and an increased focus towards flexibility of the national grid, including BESS.

As an island, the **United Kingdom** must take steps to secure its energy supply. Although the current UK energy system is still able to cope, a number of expected impacts haven been identified by Carbon

---

[10] The SDE+ (Stimulering Duurzame Energieproductie/Encouraging Sustainable Energy Production) is an operating grant. Producers receive financial compensation for the renewable energy they generate. Production of renewable energy is not always profitable because the cost price of renewable energy is higher than that of energy derived from fossil fuel. The difference in cost price is called the unprofitable component. SDE+ compensates producers for this unprofitable component for a fixed number of years, depending on the technology used. [RVO 2016]

trust and Imperial College [Carbon trust 2016] resulting from increases in RES integration in the medium and long term. These include: increased need for additional balancing power; increased need to maintain sufficient capacity margin; increased need for flexibility to maintain system reliability; reduced efficiency of conventional plants which are being displaced by VRES and localized distribution network impacts (i.e. reverse flows, congestion,…).

In its Future Energy Scenarios [National Grid 2015a], National Grid also highlights the expected increasing operational challenges the UK energy system will face. Future summers will see periods of low demand due to the increasing amounts of small scale generation. In their "Consumer Power" scenario, demand seen on the transmission system will be as low as 16.7 GW on some days by 2020, which will cause system balancing challenges. Minimum demand could even fall below 5 GW by 2030, which is below the expected level of inflexible generation by that time. Within this context, they certainly see a role of energy storage, including BESS.

The energy scenarios also show that capacity margins, whilst narrow, continue to be manageable until 2018/2019 when the capacity market is expected to deliver new sources of capacity [National Grid 2015a]. During winter months additional capacity might however be needed to support the system during periods with tight margins until the capacity market will be implemented. National grid has therefore contracted demand side balancing reserve (DSBR) and supplemental balancing reserve (SBR) for the winter of 2015/2016 [National Grid 2015a].

In the framework of its System Operability Framework [National Grid 2015b], National Grid further stresses that system inertia continues to decline under all scenarios because of the lack of synchronous thermal power stations and the high volume of converter connected generation technologies such as solar PV, wind and import across the interconnectors. The analysis shows a need for new services to manage the system frequency, as the frequency response requirement will increase by 30-40% in the next five years. This trend continues and the response requirement in the period between 2025 and 2030 will be 3-4 times higher than the current level with limited access to currently available services. New frequency response providers must be sought to meet the frequency response requirements projected for the future.

Regarding system strength and resilience, National Grid further argues in their System Operability Framework [National Grid 2015b], that the natural support to the grid is reduced and whilst converter connected technologies have some capabilities to provide the necessary support (such as dynamic voltage control) such capabilities must be further utilized. Amongst those, greater access to the services from different flexibility options including storage is necessary. This is particularly important in the context of voltage containment as it has been challenging for a number of years and studies show a significant increase in need for additional reactive compensation over the next 20 years. System restoration capability has also been reviewed in the context of unavailability of generation capable of black-starting the system and the behaviour of embedded generation during the black start.

Because of its central location in Europe, **the Netherlands** is attractive for producers' investment plans. Based on the Security of Supply and Monitoring report [TenneT 2012], the electricity generation in the Netherlands is expected to increase to a capacity of 13 GW during the period up to 2019. Due to this increase in generation capacity, the Netherlands will have an increasingly important role in the energy market of Northwest Europe in safeguarding the security of supply and facilitating the transition to a sustainable energy supply.

The growth in capacity is also leading to more export opportunities and therefore a higher potential for market coupling. This is one of the reasons for the expansion of the transmission grid by TenneT, the TSO in the Netherland. The past year already the link to the United Kingdom, BritNed, was successfully taken into operation. Furthermore, market coupling arrangements with countries in Northwest Europe and Scandinavia were made. TenneT is also working on new interconnectors. A fourth interconnector with Germany, of which a provisional decision was published in July 2012, will result in an increase of 1.5 GW of the total interconnection capacity. Also new studies are performed on subsea cable links to Norway and Denmark. As a result of the growing role of interconnectors, TenneT is increasingly realizing its strategic aim of developing the Netherlands into the 'power hub' of Northwest Europe and contributing to a level playing field. This will increase the stability of frequency in Northwest Europe. With more interconnectivity the need for storage reduces.

For distribution grid operators in the Netherlands *Stroomversnelling* [Stroomversnelling], a deal made by housing associations and construction companies, results in higher pressure on the distribution grid. In this deal the buildings in a neighbourhood are renovated to fully electric zero energy buildings. The ambition is to renovate 111,000 buildings before 2020. This results in highly insulated buildings with solar PV panels to generate electricity and a heat pump to heat the house. The electric peak load in these areas becomes significantly higher than what the grid was designed for and voltage stability becomes a problem due to the feed-in of solar PV [Stedin 2015]. Storage can help in these areas to reduce the peak of solar PV. This has been tested in 2012 by one of the distribution grid operators, Enexis, in a pilot project smart storage [Enexis 2015].

2.2.3 Regulation and policy

In **Germany**, the reduction in feed-in tariffs for solar PV which promotes self-consumption and the subsidy program from KfW and the German Development Bank have been instrumental in promoting the PV based residential energy battery storage program. The subsidy program has been providing a low-interest loan fund as well as a repayment grant since May 2013 to reduce the energy fed into the grid and push generators into a self-consumption energy model. Figures from Irena [IRENA 2015b] suggest that 12% of solar PV systems in Germany are now coupled to an energy storage system.

A follow-up program for promoting battery storage systems in connection with photovoltaic installations has recently started (as from 1 March 2016) and will run until the end of 2018. The program is aimed at encouraging the market and technological development of battery storage systems in conjunction with photovoltaic systems, for which it offers low-interest KfW loans and repayment bonuses from BMWI (Federal Ministry for Economic Affairs and Energy) funds. The most important features include [KFW 2016a, KFW 2016b]:

- The PV installation may feed maximum 50% of the installed capacity into the power grid (previously 60%);
- The manufacturer must provide a 10-year fair value replacement guarantee for the promoted batteries (previously seven years);

- The level of the repayment bonuses is falling over the program period, meaning that the repayment bonuses are reduced gradually from 25% to 10% of the eligible costs, depending on when the application is submitted. This is intended to incentivize manufacturers to pass on technology and production-related cost reductions to their customers.

Apart from self-consumption, providing frequency reserve power is an additional option in Germany. The four German TSOs procure their power reserves in an open, transparent and non-discriminatory market. Procurement is ensured through competitive bidding on a tender basis in the German balancing market where a large number of suppliers (generators as well as consumers) participate. There is no specific regulation for batteries to offer these services, but via pooling they can indirectly participate in the call for tenders [Regelleistung]. Different companies (e.g. Sonnen, Senec) have taken advantage of this pooling agreement by aggregating residential battery units into a large virtual storage to offer frequency reserve services in the German balancing market while passing on some of the advantages to the residential consumers, thereby enhancing the business case for self-consumption by means of solar PV combined with a battery (see section 3.1 Use case 1: Solar Self Consumption in Germany for further information).

For **Italy**, the difficulty in developing the grid at a satisfactory pace, the presence of structural congestions in some areas and the challenges brought by the growing number of RES (see above), has led to changes in the legal context.

Terna, the Italian TSO, can develop and manage distributed battery storage facilities in line with what was foreseen by the Grid Development Plan. The same can be done by distribution system operators (DSOs) on their own grids. This is considered not to be against the rules of unbundling of generation and transmission/distribution activities. [D.LGS 93/11] AEEG, the national regulatory agency, has provided legal ground for pilot projects with batteries connected to the transmission grid, in order to assess different solutions and improve public knowledge on the issue, before taking long term binding decisions [ISPE 2015]. On this basis Terna has launched a major investment plan, testing battery technologies on five locations with energy and power intensive applications. Capacity already installed or under construction is equal to 75 MW [Terna 2016].

In the meanwhile, progress has also been made concerning the legal framework for storage solutions connected to the grid by non-regulated actors, i.e. by energy producers or by end-users. With the amendment in December 2014 of the technical standards, which basically extend to storage facilities the same requirements introduced in the previous years to distributed generation units, and with the adoption in April 2015 of the new implementing procedures by GSE, rules for batteries owned by energy producers and final consumers have been laid out and the market for batteries in Italy seems ready to take off [ISPE 2015].

In the **United Kingdom**, storage has been identified as one of the eight technologies that support UK science strengths and business capabilities and which are anticipated to propel the UK to future growth in light of their potential to save money and reduce emissions [UK GOV 2013]. Although the potential benefits of storage have been established, support remains focused on innovation funding and demonstration projects, rather than through a policy instrument such as incentives, due to the relative infancy of some storage technologies. Most of the current projects received support from the Low

Carbon Networks Fund (LCNF) [OFGEM 2015]. The LCNF supported projects sponsored by the Distribution Network Operators (DNOs) to try out new technology, including BESS.

One of the challenges facing storage is the absence of a regulatory definition. Electricity storage is not recognized explicitly in EU legislation and is therefore treated as a subset of power generation. This legal uncertainty has implications for ownership and operation, and therefore business models for storage. As transmission system operators (TSOs) are prohibited from controlling generation, this restriction extends to storage in the UK as opposed to the situation in Italy. It also results in double charging, where storage is charged for both consuming (charging) and generating (discharging) energy, impacting on operating costs and therefore profit levels. Greater regulatory clarity could improve the environment for storage, and more targeted support – for example, mandates and incentives – could provide certainty for early adopters in the short- to medium-term. [National Grid 2015a]

Currently, battery storage may already provide certain frequency services to National Grid. The following two response services are currently seen as relevant for battery storage by National grid: Firm Frequency Response (FFR) and Frequency Control by Demand Management (FCDM). Applicable battery storage can be connected at transmission or distribution levels. The configuration of battery storage may vary in location and capacity, but if batteries are connected at different locations an aggregator has to be able to respond in a coordinated with its virtual storage [National Grid 2015c]. In addition, National Grid will procure a new faster-acting service - Enhanced Frequency Response (EFR) - aimed predominantly at storage assets including BESS to provide frequency response in 1 second or less to improve management of the system frequency pre-fault through a tendering exercise within the summer 2016 [National Grid 2016]. Two interesting facts for Battery storage are that National Grid is considering 4 year term contracts and aggregation of multiple smaller sites is allowed as long as the service provision is unaffected [National Grid 2015d][11].

As part of the government's Electricity Market Reform package, the future UK Capacity Market will ensure security of electricity supply by providing a payment for reliable sources of capacity, alongside their electricity revenues, to ensure they deliver energy when needed [UK GOV 2014]. New technologies such as electricity storage could also play a role in the capacity market, but the design of the capacity market is not supportive of these technologies and auction results show that currently energy storage has been bidding unsuccessfully in the capacity market tenders. Following changes to the capacity market would ameliorate the potential for energy storage, including BESS: a specific duration for the services it is expected to perform; stack-up of different revenue sources and the recognition of the enhanced flexibility storage provides to the grid according to AES [AES 2016].

In **the Netherlands** there are no feed-in tariffs. As a result, the volatility of electricity price on the wholesale market is limited compared to countries with a feed-in tariff, like Germany, since the electricity prices will not get below zero. This reduces the potential for storage. Furthermore, storage can be used to reduce curtailment of sustainable energy sources. With a large penetration of sustainable energy, the potential for storage becomes higher.

---

[11] More information on the different frequency services can be found via: http://www2.nationalgrid.com/uk/services/balancing-services/frequency-response/.

The balancing market in the Netherlands is very market oriented and the access to the market is good. This increases the potential for storage. However, how this market will develop until 2030 is still uncertain. Experiences until now show a higher difference in price levels compared to the intra-day market. However, the frequency of fluctuations is less. Furthermore, the market size is limited, so therefore storage has to compete with other sources of flexibility. There is however currently still a regulatory barrier since once a producing system starts, it should be able to keep running which is not possible with batteries.

Currently, for small-users in the Netherlands there is a so-called "*Salderingsregeling"*. As a result of the "*salderingsregeling"* (in English: netmetering), it is possible to get the benefits of generating one's own electricity while not using it at the same time. This regulation for netting in the Netherlands for decentral generation of solar PV takes away every incentive to use local storage to maximize self-consumption from solar PV. In 2017 this regulation will be re-evaluated. It is uncertain in what form this regulation will continue. [TUDelft et al 2015]

2.2.4 Current battery deployment in the selected countries

In **Germany**, the KfW subsidy scheme has helped boost the residential energy battery market to allow self-consumption by means of battery storage and the residential segment will still see significant growth in the German battery energy storage market in the coming years. The figure below shows the estimated cumulative usable storage capacity of decentralized solar PV battery storage installed in Germany since the beginning of the subsidy scheme in May 2013. A distinction is made between solar PV batteries which have received funding and are registered within an obligatory monitoring program (dark blue), those which have received funding but are not yet included in the registry's database (middle blue) and finally an estimation of the batteries which were sold in Germany but have not received funding (light blue). Thereby the assumption was made that 55% of all PV battery systems fall under the subsidy programme. The average capacity per PV battery storage system is assumed to be 5.8 kWh [ISEA 2016].

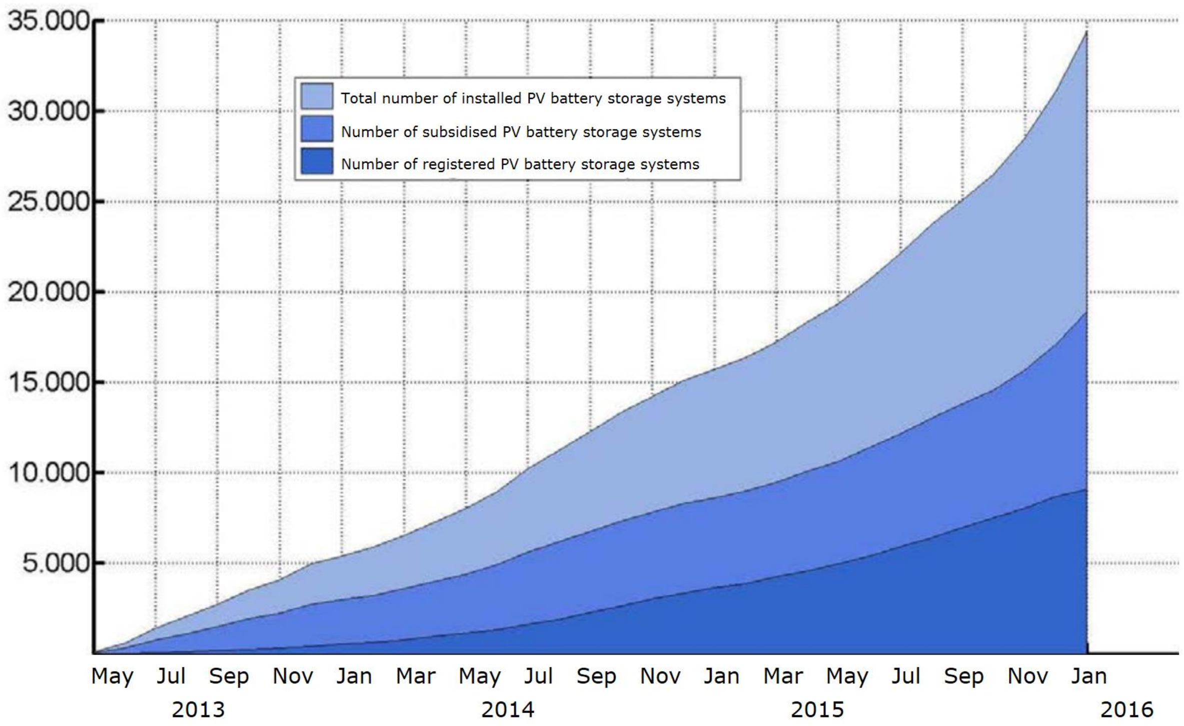
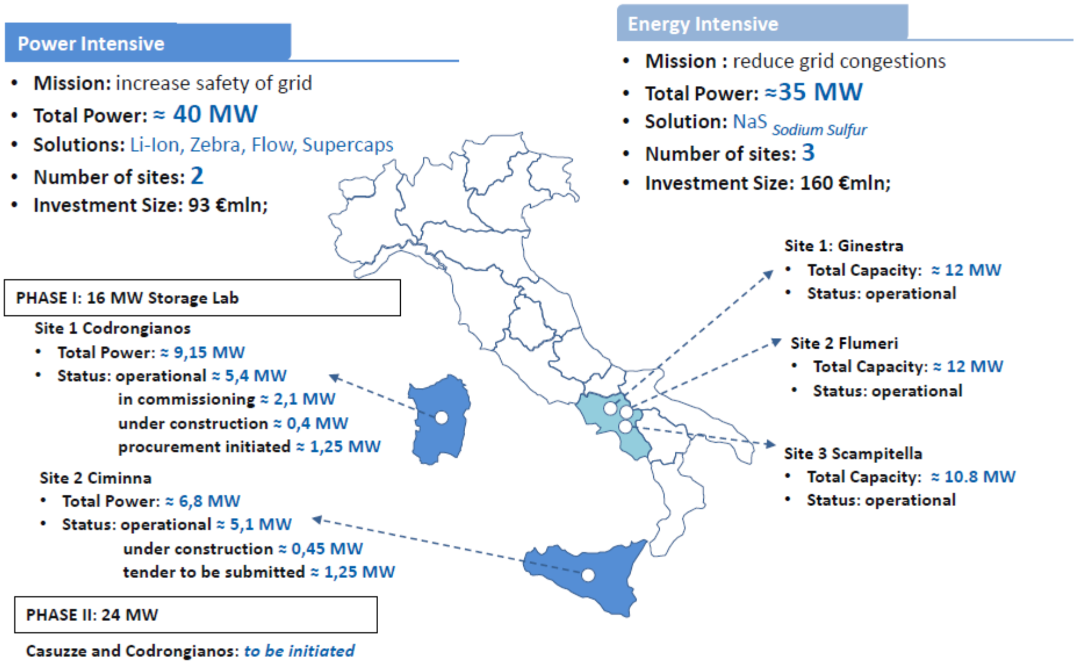


Figure 13: Estimated cumulative installed PV battery storage systems in Germany [ISEA 2016]

Moreover, Germany has currently deployed more than 20 MW of large-scale battery storage for Frequency Containment Reserves [DoE 2016] and this market is also expected to grow within the coming years, certainly when shorter-running products will be defined in the balancing markets.

In **Italy**, Terna has launched a major investment plan, testing battery technologies on five locations with both energy and power intensive applications. The focus within the islands (i.e. Sicily and Sardinia) is to increase the safety on the grid by means of power intensive BESS offering frequency reserve services and power quality services; The Italian peninsula mainly focused on the reduction of grid congestion by means of energy intensive BESS to reduce local congestions on the HV grid, while providing frequency reserve services and voltage support. The figure below gives a view on the current status of projects as part of the Terna investment plan, amounting to a total battery capacity of 75 MW, of which 24 MW is still under construction [Terna 2016]. In Italy, as far as DSOs are concerned, the situation is less developed although some investments in battery capacity by some DSOs have been done or are under way.



Power Intensive

- **Mission:** increase safety of grid
- **Total Power:** ≈ 40 MW
- **Solutions:** Li-Ion, Zebra, Flow, Supercaps
- **Number of sites:** 2
- **Investment Size:** 93 €mln;

PHASE I: 16 MW Storage Lab

Site 1 Codrongianos

- **Total Power:** ≈ 9,15 MW
- **Status:** operational ≈ 5,4 MW
  in commissioning ≈ 2,1 MW
  under construction ≈ 0,4 MW
  procurement initiated ≈ 1,25 MW

Site 2 Ciminna

- **Total Power:** ≈ 6,8 MW
- **Status:** operational ≈ 5,1 MW
  under construction ≈ 0,45 MW
  tender to be submitted ≈ 1,25 MW

PHASE II: 24 MW

Casuzze and Codrongianos: *to be initiated*

Energy Intensive

- **Mission :** reduce grid congestions
- **Total Power:** ≈35 MW
- **Solution:** NaS *Sodium Sulfur*
- **Number of sites:** 3
- **Investment Size:** 160 €mln;

Site 1: Ginestra

- **Total Capacity:** ≈ 12 MW
- **Status:** operational

Site 2 Flumeri

- **Total Capacity:** ≈ 12 MW
- **Status:** operational

Site 3 Scampitella

- **Total Capacity:** ≈ 10.8 MW
- **Status:** operational

Figure 14: Terna's Battery storage projects [TERNA 2016]

The current level of deployment of battery storage capacity in **the United Kingdom** is still relatively low with only 24 operational sites, ranging from 0.005 to 10 MW in power output and with a total installed capacity of 26MW [EUNOMIA 2016]. Six of these have been built by a single DNO, Northern Powergrid, as part of a single project. Most are 'proof of concept' projects, largely funded by the LCNF [OFGEM 2015], and either provide standalone grid services or are co-located with renewable generation. Some installations have either recently reached financial close or are under construction. The most notable is the planned 100 MW lithium-ion facility located at Kilroot Coal-fired Power Station (see below). The first 10MW of power output is now operational (as from February 2016), with plans to expand to 100 MW by 2017. As shown in Figure 15, distribution of battery storage is fairly evenly spread across the UK due to the LCNF, with each DNO taking up the opportunity to run a broadly similar demonstration project. A significant growth of battery storage in the UK is expected, with deployment taking a major step forward in 2017 as National Grid Enhanced Frequency Response contracts come on line. Moreover, due to potential attractions of behind the meter storage Eunomia expects [EUNOMIA 2016] this to be the largest growth in the short to medium term.

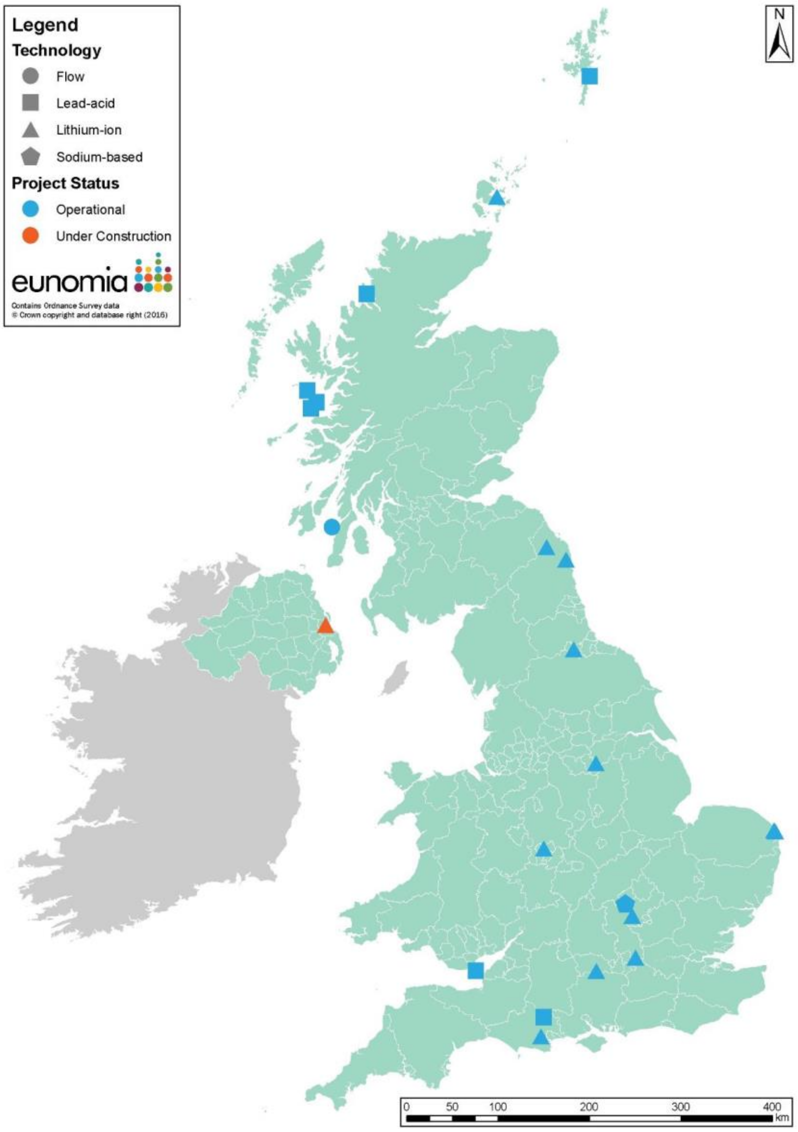


Figure 15: Location of Battery Storage Projects in the UK [EUNOMIA 2016]

In **the Netherlands** there is hardly any storage capacity installed in the distribution grid. There are however 23 pilot projects with battery storage [DoE 2016]. The reason for the limited storage in the Netherlands is the lack of a business case. Furthermore, regulation is for some cases a barrier. It is uncertain which role storage will play in the future. Recently, AES Netherlands has however introduced a 10 MW battery energy storage system in the Netherlands together with the transmission system operator. This system provides flexible power back up to the grid (10 MW for ramping up and 10 MW for ramping down) [Energy Storage News 2016]. With this system the integration of renewable energy is supported, while grid reliability is maintained. It has the potential to reduce both emissions and costs as it provides fast response balancing services to the electric grid.

Figure 16 below summarizes the battery deployment for the **four selected countries** based on installed capacity [MW] according to the different applications as identified in section 2.1.3 based on the Global Energy Storage Database [DoE 2016]. Frequency reserve services (i.e. Frequency

Containment Reserves, Frequency Restoration Reserve and Replacement Reserves) are shown as one group on the figure as the DoE database uses different and overlapping terms for the services identified in the ENTSO-E Network Code on Load-Frequency Control and Reserves [ENTSO-E 2013]. A mapping of the different services within the DoE base with the identified applications in this report can be found in Appendix B: Applications DoE – BATSTORM.

The DoE Global Energy Storage database was accessed in May 2016 to generate the figure. Some assumptions were made while using the information from the database:

1. Only projects with an operational status were used in the analysis;
2. Operational projects that were yet to be verified by project owners were included in the analysis;
3. If a project participated in several services/use cases (called Applications here), it was assumed that its rated power was equally distributed among the applications. This approach was used when sizing the current market for different energy storage applications.

The figure clearly shows that some applications are prominent as already elaborated in this section:

- In Italy projects mainly focus on voltage support, frequency reserves and grid congestion relief;
- In Germany the end-user applications are clearly mostly applied, followed by frequency reserve services;
- Finally in the UK and the Netherlands battery system mainly offer frequency reserves services.

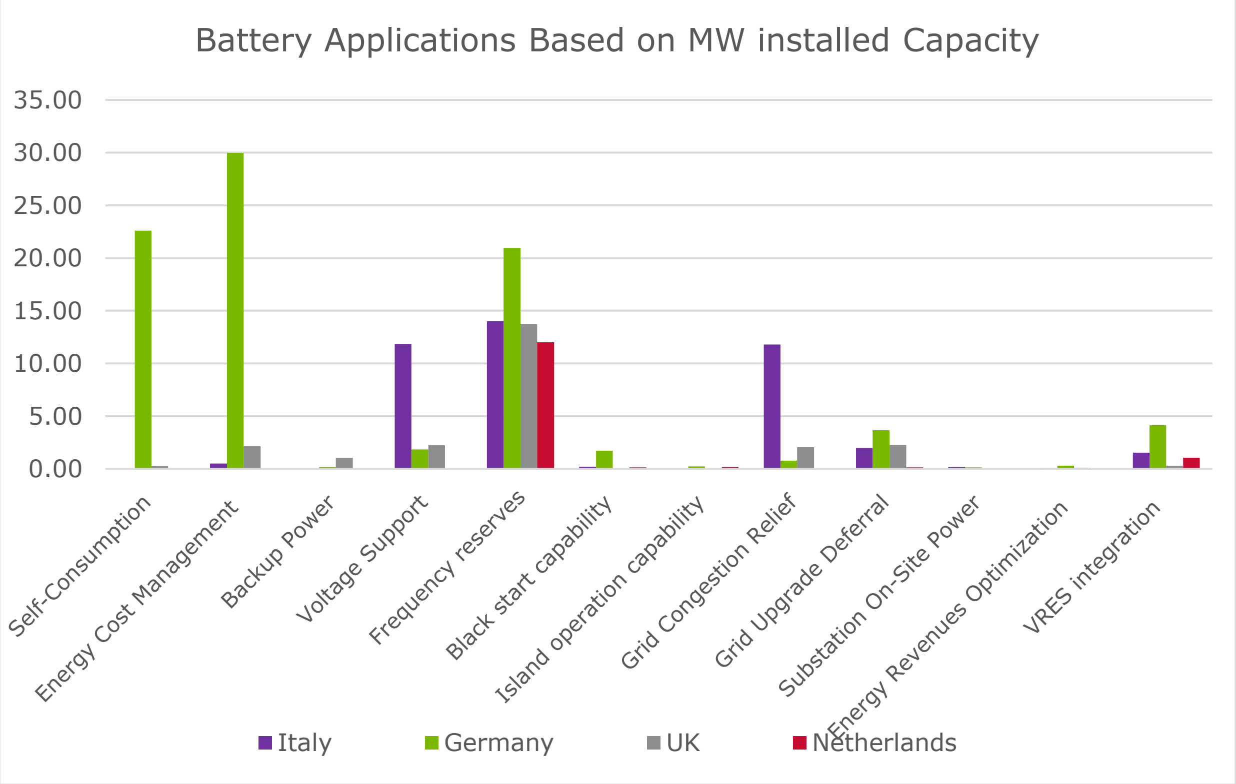


Figure 16: Battery projects serving Energy Storage Applications in the targeted countries based on MW Capacity [DoE 2016]

3 Promising business models for batteries

Taking into account the country-specific aspects identified in section 2.2 and the distribution of EU battery projects across the selected countries, we have selected a few promising battery use cases which will be described more in detail in this section. The selected use cases are shown in Table 5. The cases cover the three front running countries with respect to battery deployment. Moreover, each use case belongs to one of the four main application categories, i.e. End-User Applications (self-consumption), Ancillary Services (Frequency reserves), T&D System Applications (Grid upgrade deferral) and Renewable Generation applications (RES applications). Finally, they cover the different potential ownership models for battery storage. Appendix C: Energy Storage Ownership Models gives an overview of the different potential ownership models.

Table 5: Selected use cases for BESS in the selected countries

Applications	Country	Ownership Model	Rated Power
Solar Self-consumption at the residential level	Germany	Customer Owned	2 to 10 kWh
Merchant providing Frequency Reserves	Ireland (UK)	Third Party Owned	1 to 100 MW
Grid upgrade deferral	Italy	System Operator Owned	1 to 20 MW
VRES integration	Italy	Third Party Owned	1 to 20 MW

3.1 Use case 1: Solar Self Consumption in Germany

The robust growth of rooftop solar in Germany has been largely driven by the Feed-in-Tariffs introduced in the 1990s. Funded by an EEG[12] surcharge[13] to spur the growth of renewables, many of the feed in tariff agreements are now coming to an end. More and more German customers are trying to increase self-consumption and exploit the full potential of their rooftop PV systems as feed-in tariffs decrease. This is driving the value proposition of residential energy storage for solar self-consumption.

Today, Germany is among the leading global markets for residential energy storage. This is also driven by low interest loans and a 30% investment grant provided by the German state owned development bank KfW (see above). It has been estimated that by the end of 2015 about 21,833 to 26,200 residential energy storage installations would have been installed across Germany [GTAI 2015].

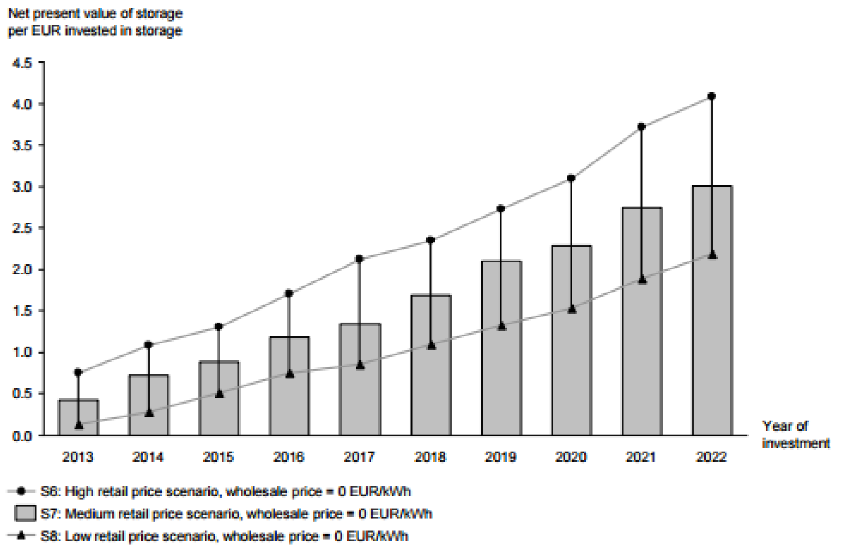
Further, energy solution providers are exploring aggregation of energy storage systems as a means for providing capacity reserve for the wholesale and ancillary service market. This stacking of energy storage applications is increasing the value proposition of residential energy storage for customers in Germany.

Use Case 1: Solar PV Self Consumption and Aggregation at the Residential Level	
Location:	Germany
Technology type:	Lithium Ion

---

[12] Erneuerbare Energien Gesetz, (Renewable Energy Surcharge).

[13] The EEG-surcharge is the mechanism that finances the feed-in tariffs. It is the difference between the wholesale market price for power on the electricity exchange and the higher fixed remuneration rate for renewable energies.

Rated System Size of Existing Projects in Germany:	2kWh to 10kWh
Services provided:	Solar self-consumption, aggregated system to provide frequency reserves
Value Proposition:	– **Self-Consumption**: Higher solar utilization – **Energy Cost Management**: Potential source of revenue for Feed-in-tariff customers, where the rates are dropping below retail power rates or simply expiring. – **VRES Integration**: Absorb grid capacity under negative pricing conditions. – **Aggregated reserve capacity**: Provide dispatchable, flexible resources to transmission system operators.
Cost Benefit Ratio of Application	 **Figure 17: Profitability index for Energy Storage for Self-Consumption [Hopmann et al. 2014]**
Ownership model:	Customer owned, Third party dispatch (Aggregated systems)
Funding:	30% investment grant available if purchased through KfW program 275[14].
Regulatory context:	– Extension of residential energy storage subsidies (in 2015 30% investment grant). – Dropping feed-in tariff rates[15] is increasing the value of storing energy when compared to selling it to the grid. – **Feed-in-Limit**: Current EEG stipulates that small scale (30kWp) residential PV battery systems with energy storage are limited to a feed-in capacity of 50% (previously 60%) of nameplate capacity. Lowering it could further incentivize storage.
Barriers to widespread development:	– High upfront costs of systems, currently only a good fit for certain residential solar customers. – Still limited aggregation options in existing market structures.
Drivers:	– Declining costs and increasing retail rates: Solar PV and energy storage to reach grid parity between 2016 and 2018 [GTAI 2015, KFW 2016a]. – High EEG surcharge rates is increasing the retail price of electricity making solar self-consumption more attractive. – Technology enthusiasm for early adopters.
System level benefits:	– Increased power quality, voltage support, reduces intermittency.

---

[14] Relaunched as of March, 2016, where level of repayment bonuses decreases over the program period from 25% to 10% over the program period (Applicable until mid-2018).

[15] The law includes a "degression mechanism", meaning that the remuneration for new installations drops at a rate determined in the legislation.

Examples of companies actively pursuing this space in Germany:	– Sonnen[16]: solar self-consumption and potential to “share” solar energy with Sonnen community. – Caterva[17]: provides energy management solutions which enable homeowners to rent out part of battery power to system operators to be dispatched remotely. – Senec-ies[18]: energy storage for residential PV systems, offering regulation power to German TSOs by means of aggregation of batteries – Next Kraftwerke[19]: virtual power plant – Lichtblick[20]: virtual power plant leveraging residential storage to provide capacity products. – E3/DC[21]: produces storage solutions to enable self-consumption. – Tesla[22]: residential energy storage for PV

3.2 Use case 2: Frequency Reserves in Northern Ireland (UK)

Under the EU renewable energy directive [Directive 2009/28/EC], Ireland would need to procure about 16% of its total energy consumption from renewable resources by 2020. To achieve the target, both the government of Ireland and Northern Ireland aim to procure about 40% of the electricity from renewable resources by 2020. In response to these binding National and European targets, EirGrid and SONI began the DS3 (Delivering a Secure, Sustainable Electricity System) program which is a multi-year programme, aimed at meeting the challenges of operating the electricity system in a secure manner while achieving the 2020 renewable electricity targets.

Currently, the maximum allowable system non-synchronous penetration (SNSP) level has implications for the load factor on both wind and conventional power plants and ultimately the design of appropriate market mechanisms in a deregulated industry. At present an SNSP level of 50% applies to the all-island power system. This means that non-synchronous generation (wind generation and HVDC imports) that is produced in excess of 50% limit is curtailed. The DS3 program [DS3 2014] is designed to increase the limit to 75% to meet the 2020 Renewable energy targets. This would increase the need for flexibility and ancillary services.

The ancillary services market is set to grow from €60m to €235m over the next 5 years [SEM 2014]. This signals a shift in valuing capacity to valuing flexible capacity[23].

---

[16] https://www.sonnen-batterie.com/
[17] http://www.caterva.de/
[18] http://www.senec-ies.com/
[19] https://www.next-kraftwerke.com/
[20] https://www.lichtblick.de
[21] http://www.e3dc.com/stromspeicher
[22] https://www.teslamotors.com
[23] Energy prices fell 9% from 2014 to 2015 due to falling commodity costs and increasing proportion of zero-fuel cost wind generation while the capacity potential has been reduced from 2015 to 2016 by 10%.

Use Case 2: Merchant providing Frequency Reserves	
Location:	Northern Ireland
Technology type:	Lithium Ion, Lead Acid, Sodium Ion
Rated System Size of Existing Projects in UK:	1 – 100MW
Services provided:	Frequency regulation, operating reserves
Value Proposition	– **Operating reserve**: Energy storage can capture performance revenue since they are a fast responding resource. The current market products available for energy storage in the Single Electricity Market in Ireland are [Eirgrid 2015]: - Primary operating reserve (£ 1.68/MWh) - Secondary operating reserve (£ 1.61/MWh) - Tertiary operating reserve (£ 1.34/MWh)
Ownership model:	Third Party Ownership
Regulatory context:	– 40% electricity from renewable energy resources by 2020. – DS3 program designed to help meet the operating challenges of achieving high levels of penetration. – Under current grid operations, renewable energy resources are forced to curtail when renewable energy generation exceeds 50% of total generation and receive payment for curtailed energy. – DS3 program aims to increase the curtailment limit from non-synchronous penetration such as wind from 50% to 75%, which will increase the need for Ancillary Services.
Barriers:	– Market rules are needed to define storage technology as a generation/transmission/distribution asset. – Beyond 10 MW, energy storage resources face additional interconnection requirements which increases the costs for developers.
Drivers	– Robust ancillary services market with new products currently being designed for fast responding regulation. – Emergence of pay for performance metrics and settlement for resources that can follow the dispatch signal. – 40% renewable electricity target by 2020 set for Ireland, which will drive the frequency regulation market.
System level benefits:	– Renewable Integration: Most economical way of integrating renewable energy resources such as wind which are often subject to curtailment. – Reduce peak capacity requirements with energy storage. – Unlock value of existing renewables resources by providing improved stability to the grid thus reduce renewable curtailment. – Improve security of supply.
Examples of projects that provide frequency regulation services in UK	– Kilroot AES Energy Storage (Lithium Ion System – AES – 10 MW) – Smarter Network Storage (Lithium Ion – Younicos – 6 MW)

3.3 Use case 3: Grid Upgrade Deferral in Italy

Under the EU Directive [Directive 2009/28/EC], the Italian Ministry of Economic development submitted the "National Action Plan for Renewable Energy" in June 2010. [NREAP IT 2010] Through its implementation, Italy intends to increase its renewable electricity production share to 29% by 2020.
The localization and rapid growth of renewable energy resources is leading to grid congestion issues; 96.6% of the installed wind capacity and 37% of the installed solar capacity [ENI 2016] is located in the south where the grid connection is traditionally weak and during periods of high production, the renewable resources fail to provide all their energy to the electricity grid due to poor transmission capability. As a result, curtailment is common.

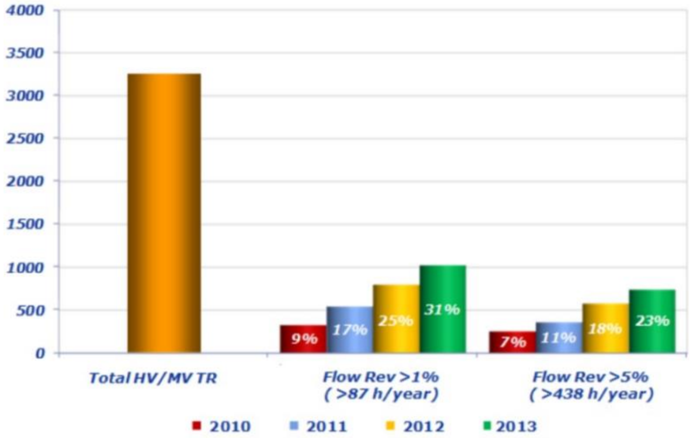


Figure 18: Energy Flow injected to Transmission Grid

Further, the high production of renewable energy is increasing reverse power flow where the power flows from a Low Voltage/ Medium Voltage line to a High Voltage line. Since the grid isn't designed to accept electricity from the distributed resources, this causes several problems. As seen from the figure below, all 14 critical areas are located in the southern and central part of Italy where maximum renewable penetration is seen.

Figure 19: Critical areas facing reverse power flows in Italy (update 30/06/2011) [ENEL 2015]

Energy Storage can effectively support the distribution grid and to a large extent alleviate issues arising from the massive penetration of distributed generation. It can be used to replace more expensive interventions, such as transformer replacements in substations which face overloads only for few moments in a year.

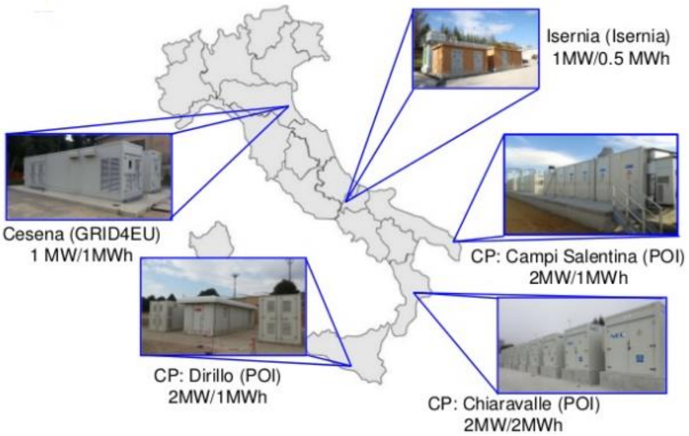
Use Case 3: Grid Upgrade Deferral	
Location:	Italy
Technology type:	Lithium Ion, Sodium-nickel-chloride Battery, Vanadium Redox Flow
Rated System Size of Existing Projects in Italy:	1 – 20 MW
Services provided:	Transmission & Distribution Upgrade Deferral
Value Proposition	Energy Storage can provide the following benefits [BIP 2013]: – **Deferral investment for transformer replacement** – **Reducing forecast error of the energy transits**: quantified by the spread between the price of energy on the day ahead market MGP[24] and balancing market MB[25] – **Reduction of reactive energy in transit on the grid**: quantified as the penalties provided by the TSO for the use of reactive power from the High Voltage grid
Benefit / Cost Ratio[26]	Varies between 0.18 to 0.22 [AEEG 2013a]
Ownership model:	System Operator Ownership
Breakeven Cost	264 € / kWh installed [BIP 2013]
Regulatory context:	– Transmission and Distribution System Operators can install and manage distributed electricity storage systems [D.LGS 93/11] – Terna has launched BESS tests on national transmission and distribution grids.
Barriers:	– Increased meshing of southern Italy is reducing the economics of energy storage as an option for grid upgrade deferral
Drivers	– Increased penetration and localization of renewable resources. – Inadequate infrastructure improvements to handle reverse power flow conditions.
System level benefits:	– **Reduction of reverse flow**: Energy storage can contribute to improving the quality of supply and voltage. – **Decrease of grid congestion:** The central-southern and peninsular region have higher congestion problems owing to a lower level of meshing and limitations in transmission capacity. – **Improve power quality and reliability of distribution system** – **Decrease Renewable Energy Curtailment**
Examples of projects that provide grid upgrade deferral services in Italy	– Energy storage projects that are connected to the high voltage grid: see Figure 14. – Energy storage projects that are connected to the medium voltage distribution grid [ENEL 2015]

---

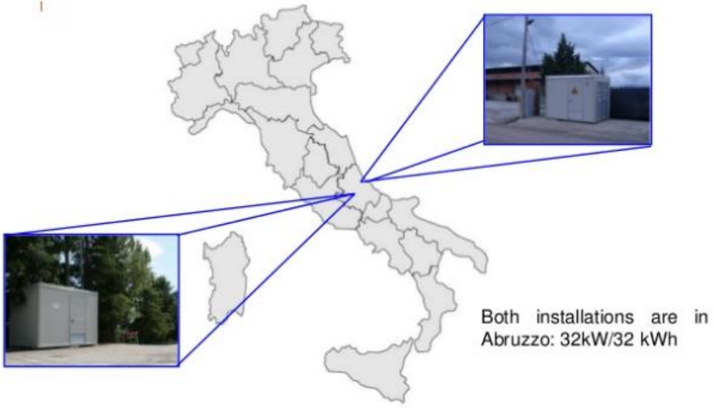
[24] "Mercato del Giorno Prima", Day Ahead Market

[25] "Mercato di Bilanciamento", Balancing market

[26] Calculated as:
Avoided Energy Custailment to RES in the Area * Chare/Discharge Efficiency* Price of Energy / (Total Project Cost OPEX+CAPEX)



- Energy storage projects connected to low voltage distribution grid [ENEL 2015]



3.4 Use case 4: Variable Renewable Energy Service Optimization in Italy

As mentioned above, Italy intends to increase the share of renewable energy to 29% of the gross final consumption in the electric power by 2020. Renewable energy resources are granted a higher dispatch priority and currently, are not penalized for failing to meet their production programs. As a result, renewable energy producers have no obligation to present a reliable program and this may largely impact the grid. To avoid this AEEG provides an incentive[27] that is inversely proportional to the absolute value of the difference between the production program and the actual production. Energy Storage can effectively be used to capture these incentives by optimizing the production profile and thus reduce the forecasting errors. [Eclarion 2011]

Use Case 4: VRES Energy Optimization	
Location:	Italy
Technology type:	Lithium Ion, Vanadium Redox, Sodium-Nickel-Chloride
Rated System Size of Existing Projects in Italy:	1 – 20 MW
Services provided:	VRES integration, Energy Revenues Optimization from RES
Value Proposition	– **Reduction of forecast errors** (minimizing imbalances)

---

[27] For non-programmable RES-E plants over 10 MVA, (AEEG Resolution 05/10)

	– **Improve energy recovery from power plant limitations** (due to TSO order for imposed limitations when transport capacity is less than the maximum output power from the plants) – **Energy time shift and grid integration:** Storage systems can be operated in order to adopt a time shift strategy, with energy accumulation when the price is low and energy sale during peaks.
Ownership model:	Customer Ownership
Energy Storage Breakeven Cost	360 €/kWh (2013) [BIP 2013]
Regulatory context:	– Transmission System Operator and Distribution System Operator are allowed to o Install and manage distributed storage systems [D.LGS 93/11] o Include electrical energy storage systems in its Development Plan, aimed at facilitating the dispatch of non-programmable RES plants. [D.LGS 28/11] – Terna has established transitional provisions for the application of the imbalance penalties to Renewable Energy production units in order to reduce costs due to poor predictability of such systems [DEL.281/2012/R/EFR]. – Under the AEEG's 613/2013/R/eel proposal document, batteries must be considered as production facilities [AEEG 2013b]
Barriers:	– High installed cost for energy storage – Unable to participate in balancing market [EFET 2014] – Distributed renewable resources plants are excluded from the primary/secondary/tertiary reserve obligation
Drivers	– Renewable Energy Providers are required by TERNA to keep 1.5% of their peak capacity for primary reserve (No remuneration for this provision), as a result the maximum the operator can be paid for is 98.5% of their peak capacity. To capture additional value of their renewable resources, operators couple them with batteries to increase revenue.
System level benefits:	– Reduced Curtailment of Renewable Energy
Examples of projects that provide VRES Optimization in Italy	– Enel Livorno Test Facility – GRID4EU Demo 4: Enel RCube – Smart Polygeneration Microgrid, University of Genoa – Tozzi Energy Storage System - TESS

4 Battery cost development

Any assessment of batteries, must be coupled with a cost analysis. A BESS is comprised of several components. These include battery cells (for cell-based batteries), a power conversion system, materials in the module, a battery management system and other components. In addition, labour, maintenance and other variable costs must be taken into account. While individual cell costs (for cell-based batteries) may be a good economic indicator for comparison purposes, they only represent around 20% of all relevant costs. [IRENA 2015a] Total system and variable costs depend on location, application, additional equipment needed, vendors, commercial availability, size of the system and other variables. Within this section, we will focus on current projected battery investments costs at the battery system level for the main battery technology categories based on several sources.

Battery costs, particularly Lithium-ion, have demonstrated a significant cost reduction over recent years. The reductions have mainly been driven by economies of scale and continued improvements of existing technologies. The volume drivers today are mostly consumer applications and increasingly electrical vehicles and to a lesser extent energy system applications [INSIGHT_E 2014]. Energy system applications can of course benefit from these developments since characteristics of battery cells are similar. For the most prominent applications (e.g. home batteries), economies of scale and cost reduction based on experience are also expected for batteries within energy system applications.

The following graphs give an overview of past, current and projected costs of battery systems based on different sources. [IRENA 2015a, Bloomberg 2016, EPRI 2010, EIA 2012, RMI 2014, Roland Berger 2012, Deutsche Bank 2015, Castillo et al 2014, Zakeri et al 2015, Lazard 2015, JRC 2014a] A separate graph is made for the main battery technology categories. The different cost estimations date from 2010 to 2016. Most of these sources give prices at battery system level. Only the projected costs by IRENA [IRENA 2015a] are on cell level. The different sources cover batteries aimed for residential, commercial and industrial end-users, batteries at grid level and batteries co-located with VRES. Within the graphs, no distinction is made according to location. Moreover, some sources give different prices for different applications i.e. [EPRI 2010, Lazard 2015, JRC 2014a], while some studies give ranges (a high and low value); These values are all shown as separate data points on the graphs, so that for a given year, source and technology, multiple values might be displayed. As can be seen, projected battery costs from the different studies show a large variation, so the figures can only be used to indicate overall trends and draw general conclusions. A more detailed analysis of price differences per technology based on size, location and application is not within the scope of this analysis.

Figure 20 shows the cost projections for **lead-acid batteries**. The cost estimates in the first years show a rather large spread. This is mainly due to the wide variety of applications that were taken into account. As explained in section 2.1.4, lead-acid batteries are typically less suitable for services that require fast reaction (e.g. Frequency Containment Reserve). For these applications, systems are typically over-dimensioned, leading to relatively high costs. From 2020 onwards we see only very minimal evolution in the costs, mainly because the lead-acid technology is a very mature technology in which developments are evolutionary rather than revolutionary (e.g. lead-carbon, lead-crystal…).

Projections for **Lithium-ion batteries** are given in Figure 21. In the first year, the EPRI figures show an extraordinary broad range (Deutsche Bank reference is taken from EPRI) with the highest cost estimates related to the most demanding (Frequency Containment Reserve) or small-scale applications (residential/distributed energy storage). Figure 22 shows the same information without the EPRI and Deutsche Bank sources. These data show very good consistency, with system prices reaching the €200/kWh mark around 2035 as can also be seen in Figure 23 which gives a snapshot of the same figure but only displaying the values <€1000/kWh. With developments in Li-ion technology and related technologies (LiS, Na-ion…) still ongoing, there is a good basis for a continued cost evolution over the next decades.

For **Nickel-based batteries** (NiMH and NiCd, no NiFe) the amount of sources is limited (see Figure 24). The Roland Berger figures are based on the EV application, whereas the Aalto figures focus on grid applications. This explains the difference between these figures. No long term estimates were found. However short term evolution shows a significant cost decrease. If this trend continues (indicated in the dashed trend line), the cost could be around €200/kWh in 2030 and significantly below €100/kWh in 2050. However due to the relative maturity of Nickel-based battery technology, it can be questioned whether this projected steep cost decrease will continue on the long term.

For **metal-air batteries**, the amount of sources is also quite limited as can be seen in Figure 25. The most extensive source (Lazard) treats a wide variety of applications, which clearly show a lower cost for large-scale applications (e.g. transmission grid support, peaker replacement…) with a steeply increasing cost for smaller scale applications (industrial, micro grid, etc.). When comparing on an application by application basis, the figures show a consistent 5% cost decrease in 5 years (2015-2020). If this trend is correct and if it continues into the future, this would lead to costs around €150/kWh in 2050. However due to the relative immaturity of this battery technology, significant developments are to be expected and good forecasts are hard to make.

Sources for **molten salt batteries** are also limited with most studies only showing price estimates for a single time period instead of an evolution (see Figure 26). The JRC and IRENA figures show a cost decrease albeit a slow decrease. All figures are based on either NaS or NaNiCl technologies, which are both fairly mature. Also for this type of batteries, the system cost (including heating infrastructure) is significant. Both aspects probably lead to this slower cost decrease, leading to a cost estimate of around €300/kWh in 2050. Nevertheless further research and development activity in this field (molten salt or molten metal batteries) may enable more significant cost decreases.

Comparable to previous charts, the cost estimates for **flow batteries** show a very broad range (see Figure 27), depending on the application, with large-scale applications (e.g. bulk energy storage) showing lower cost than smaller scale applications (residential, commercial, industrial). Since a broad range of materials is currently being used and investigated for flow batteries, the estimates are also highly dependent on the materials considered with cost estimates for Zn/Br and Fe/Cr systems being considerably lower than the estimates for Vanadium-based systems, obviously due to the cost of Vanadium. Cost forecasts show a cost significantly below €100/kWh for 2050. Considering all kinds of new and relatively cheap materials (Cu, Fe…) currently being researched and investigated for flow batteries, this forecast is not unimaginable.

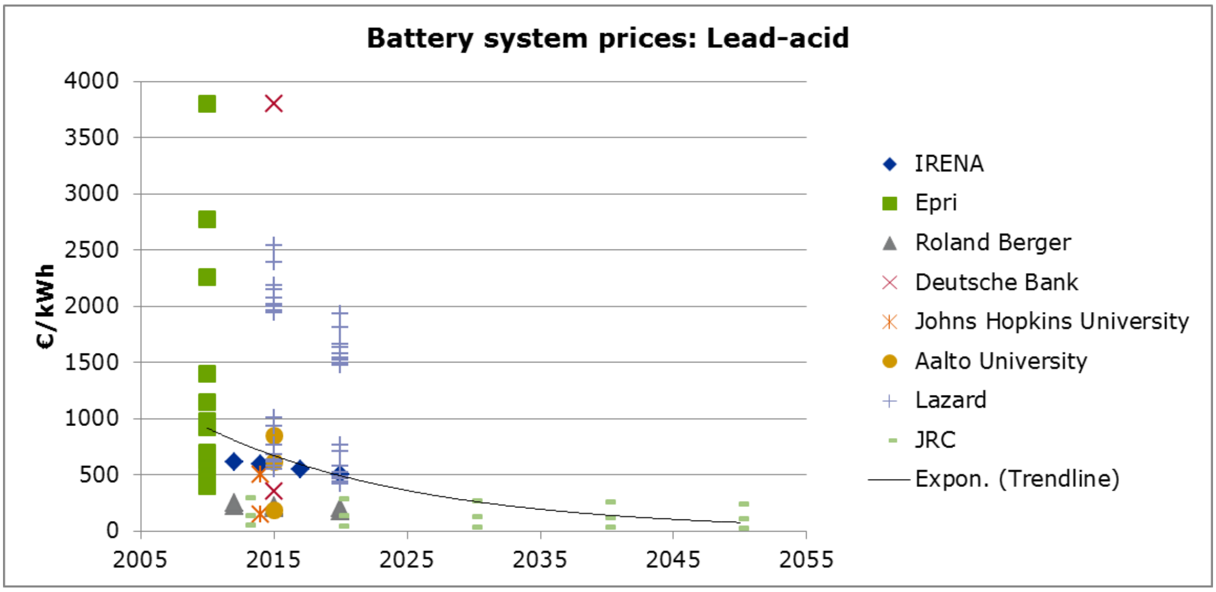


Figure 20: Current, passed and projected battery system costs for lead-acid batteries [IRENA 2015a, EPRI 2010, Roland Berger 2012, Deutsche Bank 2015, Castillo et al 2014, Zakeri et al 2015, Lazard 2015, JRC 2014a]

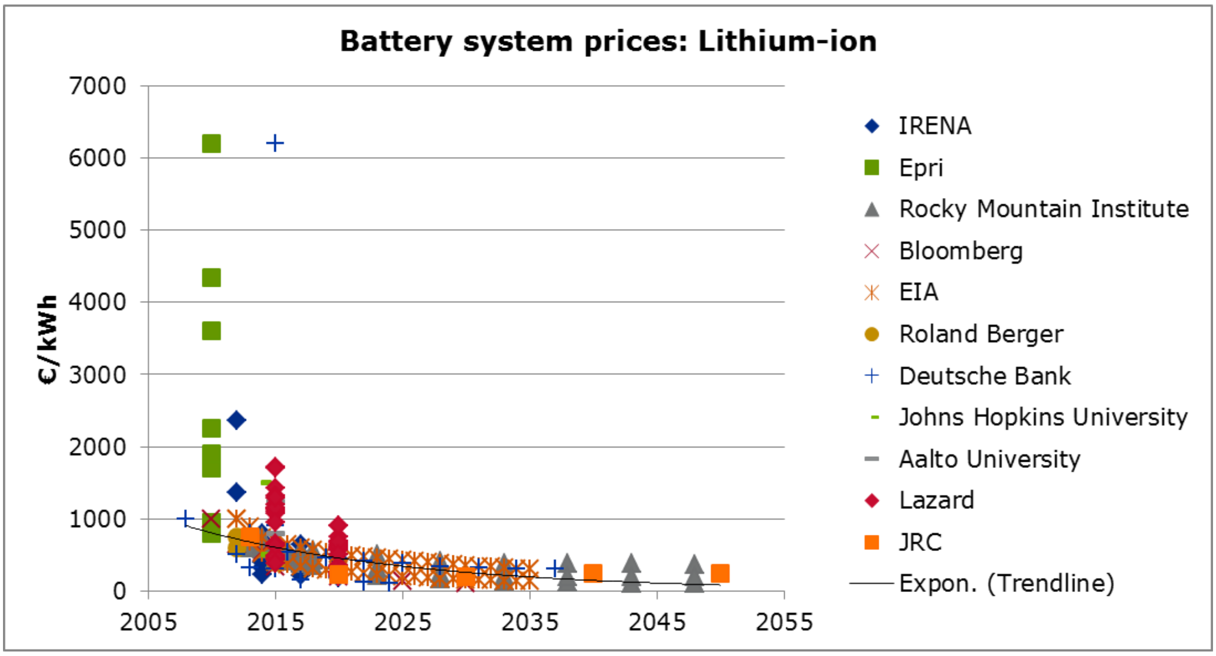


Figure 21: Current, passed and projected battery system costs for lithium-ion batteries[IRENA 2015a, EPRI 2010, RMI 2014, Bloomberg 2016, EIA 2012, Roland Berger 2012, Deutsche Bank 2015, Castillo et al 2014, Zakeri et al 2015, Lazard 2015, JRC 2014a]

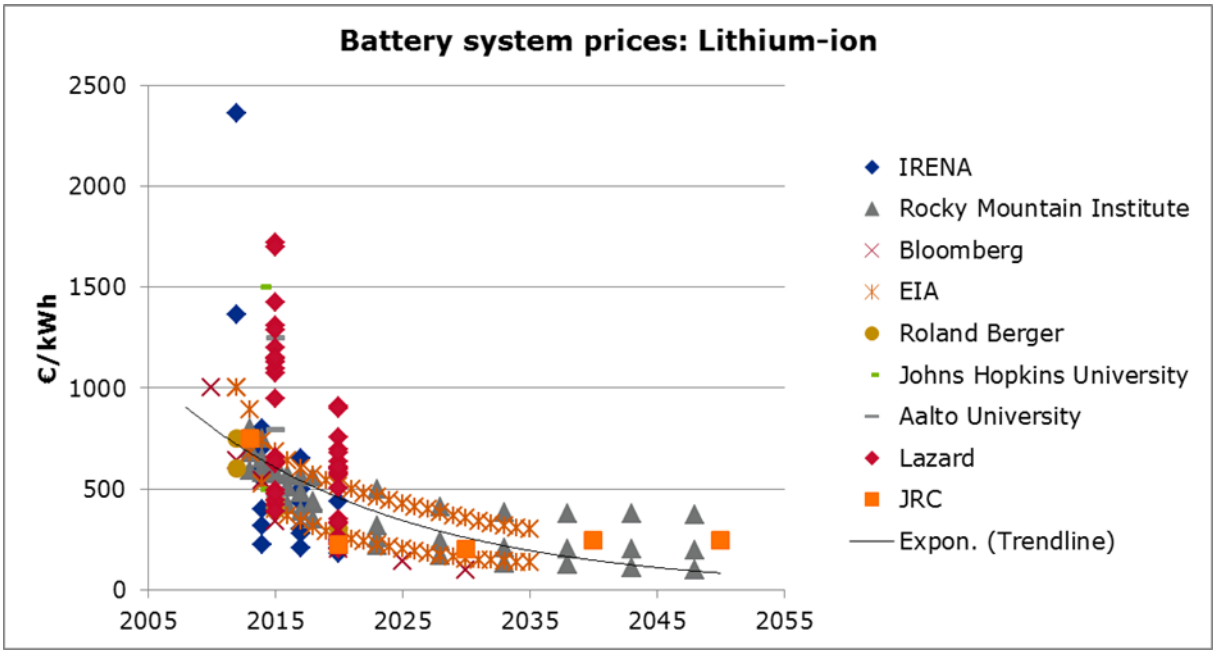


Figure 22: Current, passed and projected battery system costs for lithium-ion batteries [IRENA 2015a, RMI 2014, Bloomberg 2016, EIA 2012, Roland Berger 2012, Castillo et al 2014, Zakeri et al 2015, Lazard 2015, JRC 2014a]

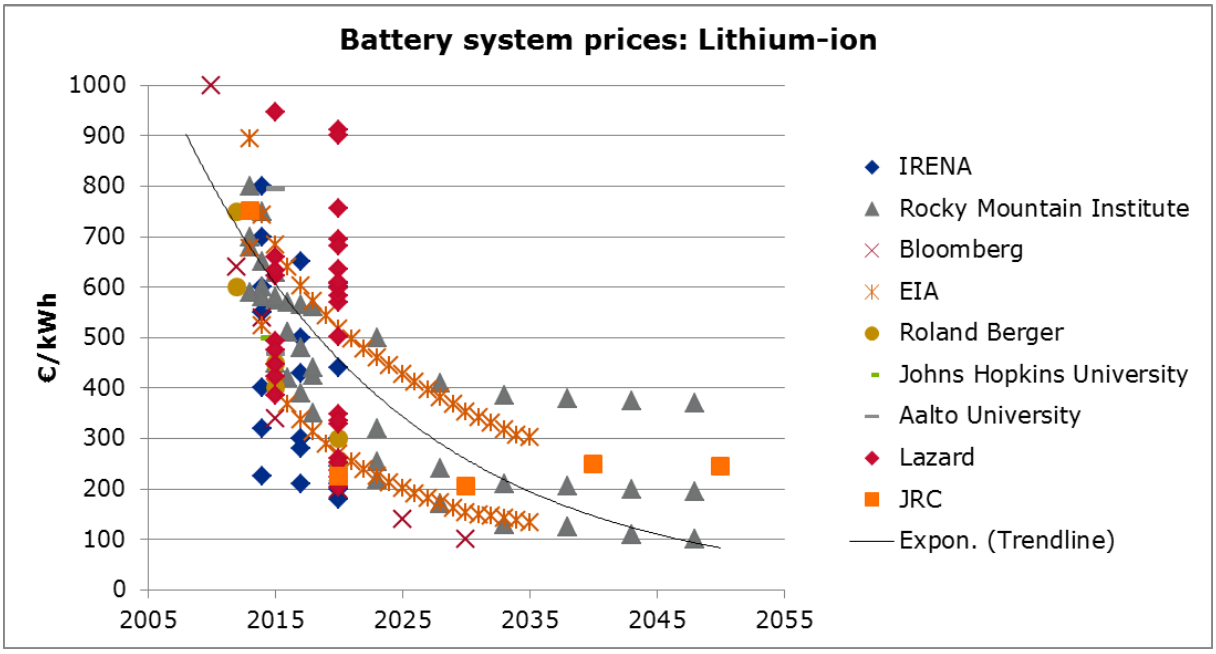


Figure 23: Current, passed and projected battery system costs (data points < 1000 €/kWh) for lithium-ion batteries [IRENA 2015a, RMI 2014, Bloomberg 2016, EIA 2012, Roland Berger 2012, Castillo et al 2014, Zakeri et al 2015, Lazard 2015, JRC 2014a]

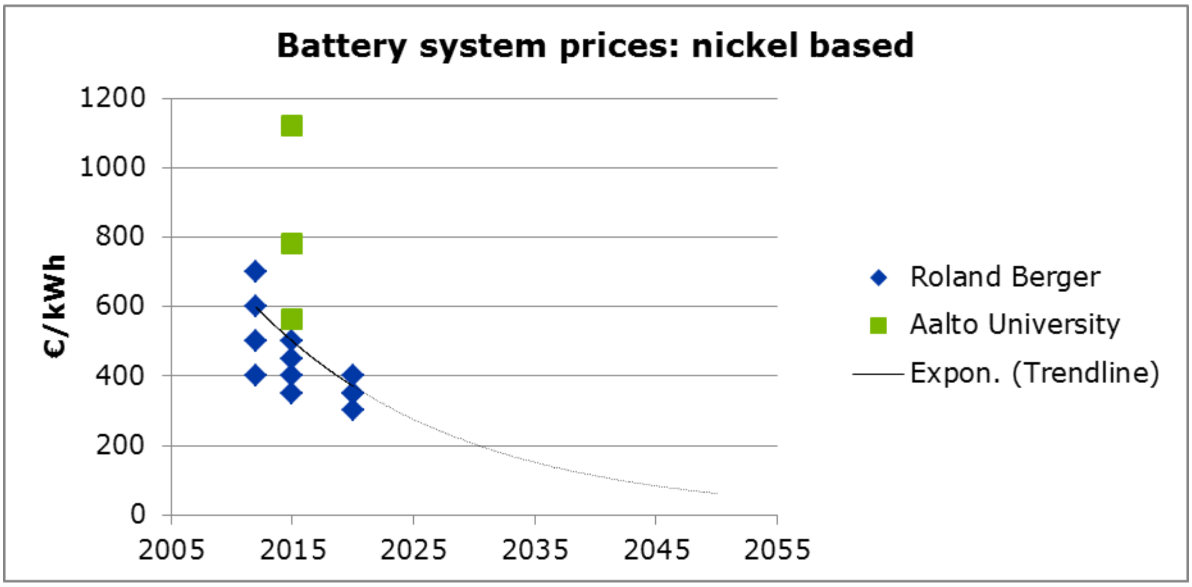


Figure 24: Current, passed and projected battery system costs for nickel-based batteries [Roland Berger 2012, Zakeri et al 2015]

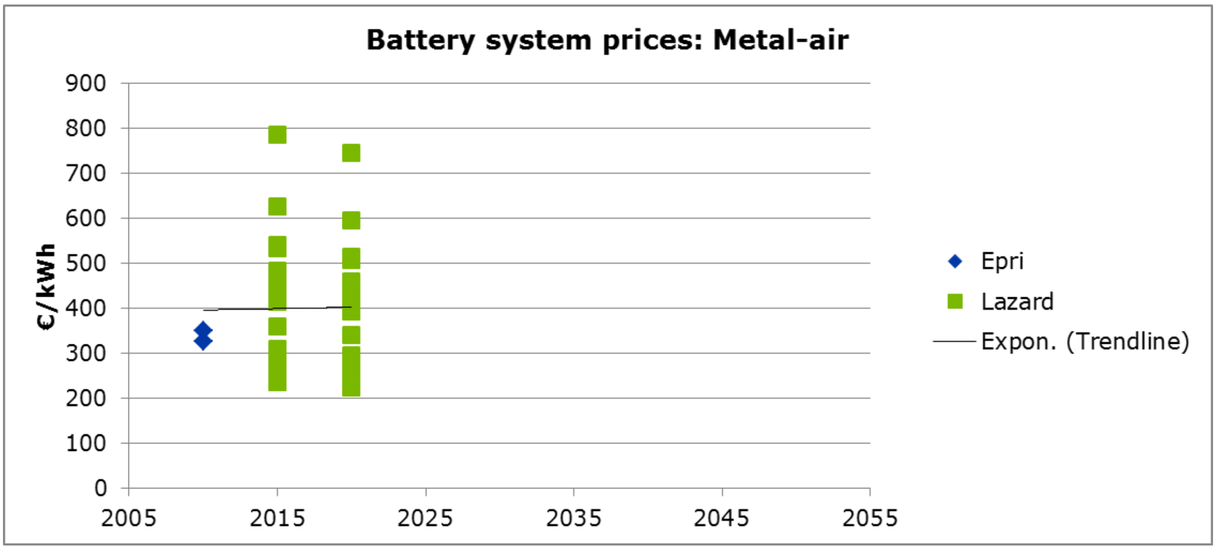


Figure 25: Current, passed and projected battery system costs for metal-air batteries [EPRI 2010, Lazard 2015]

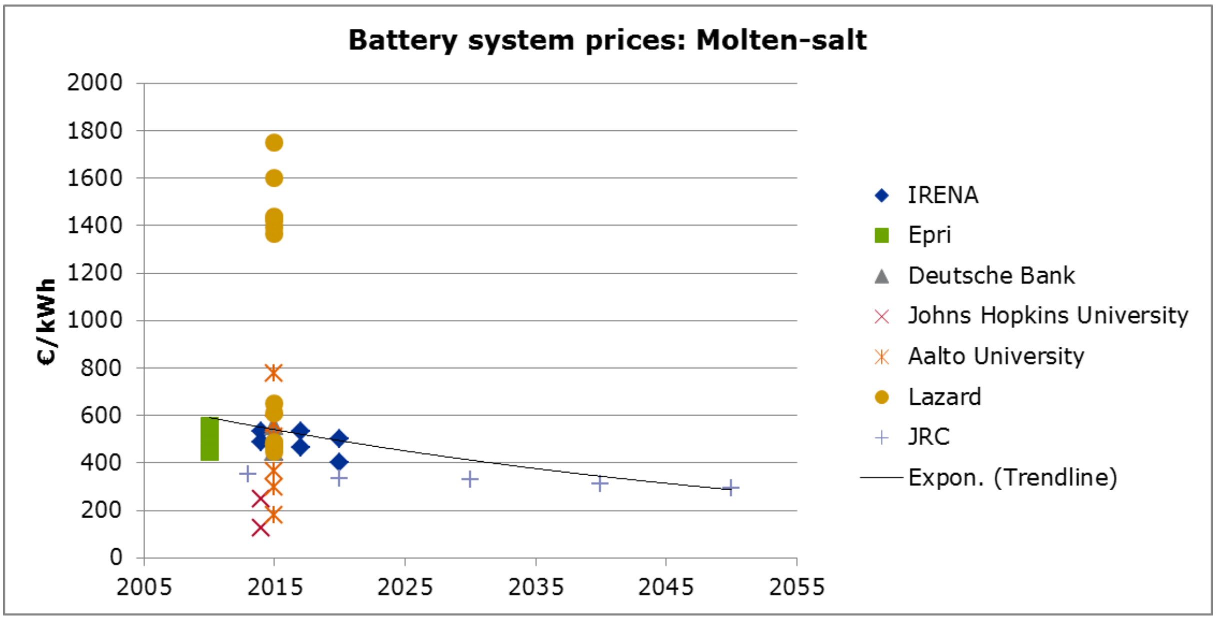


Figure 26: Current, passed and projected battery system costs for molten-salt batteries [IRENA 2015a, EPRI 2010, Deutsche Bank 2015, Castillo et al 2014, Zakeri et al 2015, Lazard 2015, JRC 2014a]

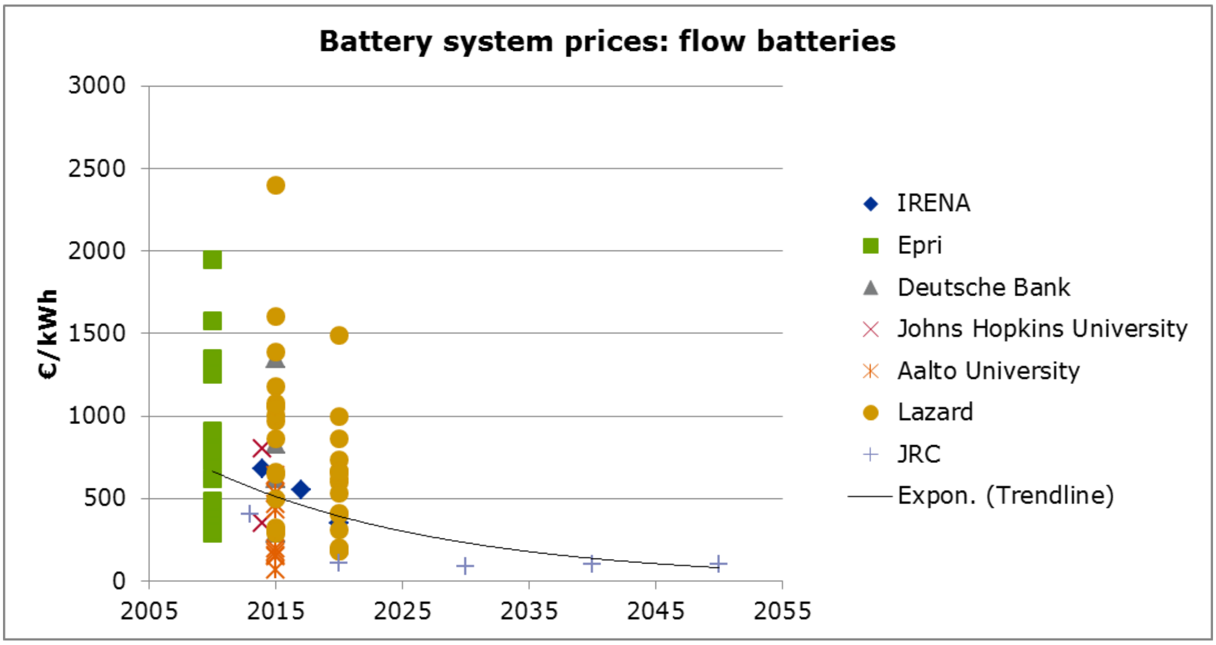


Figure 27: Current, passed and projected battery system costs for flow batteries [IRENA 2015a, EPRI 2010, Deutsche Bank 2015, Castillo et al 2014, Zakeri et al 2015, Lazard 2015, JRC 2014a]

As already mentioned in the introduction, the EC has set targets for BESS in the energy system in its issues paper 7 of the SET-plan [EC 2016a]; R&I should aim at *"developing and demonstrating technology, manufacturing processes, standards and systems, which have the potential of driving high-efficiency (>90%) battery based energy storage system cost below €150/kWh (for a 100kW reference system) and a lifetime of thousands of cycles by 2030 to enable them to play an important role in smart grids*". The references used in this section assume that battery costs of €150/kWh are only attainable by 2040 for lead-acid and lithium ion based batteries and for some flow battery technologies. Supplementary R&I might thus be needed to drive down these prices faster. Some references have more optimistic projections though. According to [JRC 2014a] battery costs below €150/kWh are already available today for Lead-acid batteries. Some studies report battery costs below €150/kWh before 2030 for lithium ion [Deutsche Bank 2015, Bloomberg 2016], while [RMI 2014] estimates costs below €150/kWh by 2033 for lithium ion. According to the sources used, the other technologies generally are not likely to reach the threshold of €150/kWh before 2030.

5 Competitive assessment of technological options

System services provided by batteries, can in most cases also be provided by other technologies. The set of services provided by each technology will be defined on the basis of competition. In order to investigate the position of each technology, it is therefore necessary to perform a comparative assessment of the techno-economic characteristics of all options.

This chapter provides such a competitive technology assessment. In a first step other flexibility options will be introduced and categorized with respect to their location, response time and energy content capability. A mapping of the introduced flexibility options to the above defined BESS applications is used to illustrate how well a competing technology can provide the defined services in comparison to battery based energy storage. A summarizing table gives an overview of which solutions are technically and economically suitable for different applications.

5.1 Flexibility options for the power system

In section 2.1.3 different services that battery storage can provide to the energy system have been discussed. For the listed applications batteries stand in direct competition to other flexibility options. The competing technologies are all able to provide flexibility services in the face of rapid and large swings in supply or demand. Those services include "up regulation" that provides additional power as needed to maintain system balance, and "down regulation" that reduces the power surplus in the system. Based on the physical assets in a system, flexibility options can be categorised into supply (generation), demand and storage options.

However, in this report we will focus only on technologies which can provide up and/or down regulation and therefore compete directly with battery storage. The figure below shows the different potential technologies that can be used to provide flexibility and that stand in direct competition with battery based energy storage. Those technology options will be shortly described in this section following [Ecofys 2014]. The next section will then assess their technical suitability to provide the battery storage applications as defined in section 2.1.3.

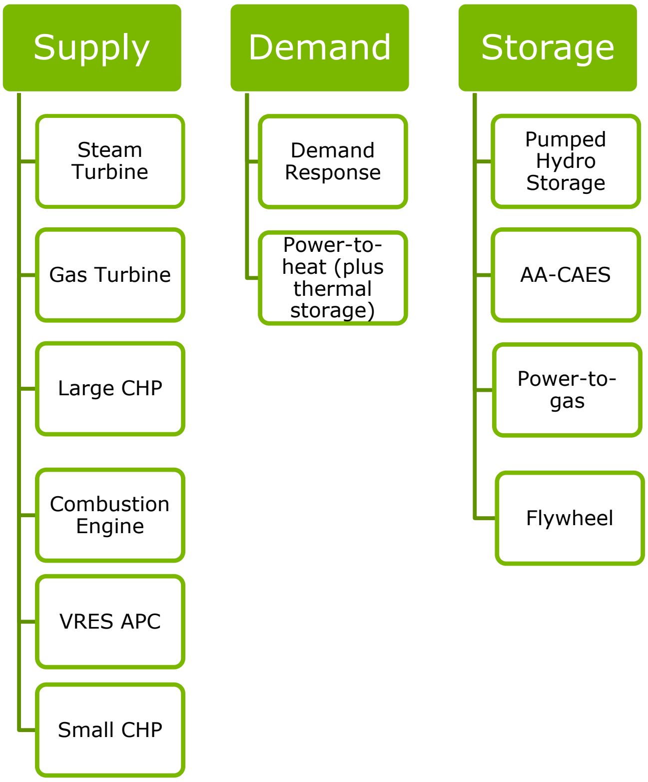


Figure 28: Flexibility options in the energy system aside from batteries

5.1.1 Supply

Traditionally, the supply side has provided almost all required flexibility to balance the fluctuations in demand. Two key tasks for the power plant fleet were to follow all variations in demand and to ensure system balance, even in case of a sudden loss of a generating unit. With increasing shares of renewable energy receiving feed-in priority, the role of less controllable conventional must-run power plants as flexibility option will be reduced while at the same time the fluctuations in the system will be considerably higher and sometimes unpredictable, requiring greater flexibility. This change in the power system creates opportunities for other flexibility options. We consider the following flexible supply options:

- **Steam turbines** use the dynamic pressure generated by expanding steam to turn the blades of a turbine. This group combines among others nuclear, coal and lignite power plants. Key flexibility constraints come from the technical restrictions of each technology, defined by its ramping capability, must-run requirements and minimum load. Technology developments in power generation and refurbishment of old units can increase the flexibility of thermal generation;
- **Gas turbines** use the expansion of combustion gases to directly power the turbine. Since gas turbines do not need any pre-heated steam to operate, they can be quickly brought online and have higher ramping rates. Gas turbines combine Combined Cycle Gas power plants and Open Cycle Gas Turbines;
- **Combined Heat and Power (CHP) plants** produce electricity and heat simultaneously from the same fuel source in a central process (mostly gas and steam turbines). Central CHP plants are usually operated heat-driven and used for providing thermal energy for district

heating or heat consuming industries. Micro-CHP are small-scale installations that provide residential heating and electricity. CHPs are highly dependent on their primary tasks (heat production) and therefore offer very low flexibility. Nonetheless if a heat storage system is applied, CHP plants can provide flexibility that reduces must-run capacity in the system and allows CHP plants to participate in offering services to the system;

- **Internal combustion engines (ICE)** use reciprocating pistons to convert pressure into a rotating motion and generate electricity. ICE are often used for power production in isolated systems (islands) as well as for emergency back-up capacity, e.g. in hospitals (decentral locations);
- **Active power control of renewable power plants (VRES APC)** refers to the adjustment of the renewable resource's power production in various response timeframes to assist in balancing the system or managing congestion. Wind turbines and PV installations have the technical capability to provide a fast response to regulation signals. By curtailing power production, these installations can provide down regulation. Up regulation can be provided, by operating units at partial load that are able to increase capacity when needed. Both operations cause an overall reduction in VRES output.

5.1.2 Demand

Demand management programs make use of new capabilities in communication and control, enabling two-way communication with loads as small as 5 kW. Such options include demand management in energy intensive industries, services and smart appliances as well as options that come from the electrification of other sectors, such as electric vehicles, heat pumps and water heating. The disadvantage of demand management is that flexibility depends on consumer willingness to shift consumption. The substantial advantage is their minimal investment costs, since they are developed for another primary purpose. A distinction is made between the following demand side flexibility options:

- **Demand management:** One can distinguish between demand management for industrial consumers and demand management for commercial and residential customers. For industrial demand, the flexibility potential is highly dependent on the process needs. Demand management can also be applied in the commercial and residential sector, especially to heating and cooling processes. To harvest the flexibility potential in the residential sector, investments in information and communication technologies are needed;
- **Power-to-heat (plus thermal storage):** Electricity can be used to provide heat substituting other fuels like gas. One option for power to heat is direct resistance heating. Another option is heat pumps where electricity is used to bring heat from a natural source (e.g. ambient air) to a higher temperature level. The thermal energy can be stored and is released by the end user when needed. The thermal storage offers the ability to flexibly adjust the heat generation in time.

5.1.3 Storage

Energy storage can be seen as both generation and demand in the system, allowing the time-shifting of energy between periods of over- and undersupply from VRES. Key options here are pumped storage, Advanced Adiabatic Compressed Air Energy Storage ((AA-) CAES), flywheels, batteries, as well as power-to-gas. The following storage technologies are included in this analysis:

- **Pumped Hydro Storage**: Pumped hydro stores energy mechanically, by using electricity to pump water from a lower reservoir to an upper reservoir and recovering the energy by allowing the water to flow back through turbines to produce power, similar to traditional hydropower plants. Pumped storage technology is mature, has low O&M costs and is not limited by cycling degradation. Capital costs tend to be high and they have very specific siting requirements. Costs are highly situational, depending on size, siting and construction;
- **Advanced Adiabatic Compressed Air Energy Storage** (**AA-CAES**) stores electricity mechanically by running electric motors to compress air into enclosed volumes and capturing the heat during compression. For discharge, the mechanical energy is fed into the inlet of a combustion turbine while the captured heat returns to the combustion turbine inlet for carbon free operation. Key barriers to the technology are its low efficiency, high capital costs and specific siting requirements. New developments also show that smaller scale AA-CAES solutions for decentral applications are possible in the future;
- **Power-to-gas** stores energy chemically, by using electricity to split water into hydrogen and oxygen by means of electrolysis. The produced hydrogen is currently used in two different ways. The first one results in injecting hydrogen directly into the natural gas grid or using it in transport or industry. The second method consists of combining the hydrogen with carbon dioxide to produce methane which is then fed to the natural gas grid or used by industrial consumers. The energy conversion efficiency of power to gas ranges between 50-70% depending on pressure medium and output gas. If electricity is to be reproduced in a power to gas to power process, than the round trip efficiency drops to 30-44%. [Energy and Environmental Science 2015];
- **Flywheels** are rotating masses that store electricity in the form of kinetic energy. Energy is transferred in and out using a motor-generator that spins a shaft connected to the rotor. To minimise the energy lost during rotation, flywheels are often maintained in a vacuum and rest on very low friction bearings (e.g. magnetic). Rotor characteristics such as inertia and maximum rotation speed determine the energy capacity and density of the devices. The motor-generator and associated power electronics determine the maximum power of the flywheel, allowing for power and energy capacities to be decoupled. Key advantages of the technology are the fast response times and the provision of inertia for grid stabilisation, while the key barrier is the high investment costs.

5.2 Competitive assessment of flexibility options

The previous section already showed that different technologies can provide different forms of flexibility. Within this section, we analyse the suitability of the flexibility options for the applications defined in section 2.1.3. Some flexibility options are well suited to provide short term flexibility with short response times which is for example needed in order to provide frequency containment reserves. Others are better suited to provide energy over a long duration which is needed for energy revenue optimization and self-consumption. Additionally some flexibility options are well suited to provide power decentrally, exactly where needed. In cases where the energy is needed close to generation, transformer stations or consumers, this is a great advantage. In order to map the different applications of batteries to competing flexibility options, the services and technologies were grouped on **location**, **response time** and **duration** of providing energy (see Figure 29 and Figure 30). These three parameters allow a better understanding of the requirements of the different applications. Furthermore, the separation between central and decentral services is crucial as many of the applications require the service at a specific location.

The requirement of a certain location can be relevant if the service needs to be provided close to production/consumption or at a specific section of the grid (distribution and transmission). This is in contrast to services that need to be provided to balance the whole system and can therefore be provided by central systems (but also aggregated, decentral systems) regardless of their location in the grid. The response time indicates how fast a flexibility option needs to respond to a system need. For some applications, a short response time is a very crucial factor; for frequency containment reserve a response within seconds is essential otherwise the frequency deviation will lead to a system failure. For technical solutions the response time differs regarding their cold start or their hot start capabilities. For example, while fossil fuel generation can ramp with up to 4% per minute to 20% per minute when in operation the duration for a cold start can take up to 10 hours and is therefore highly inflexible. With increasing shares of fossil generation used as cold reserve this should be kept in mind. The final parameter "duration" indicates how long energy needs to be provided in order to serve the application and therefore fulfil the system need.

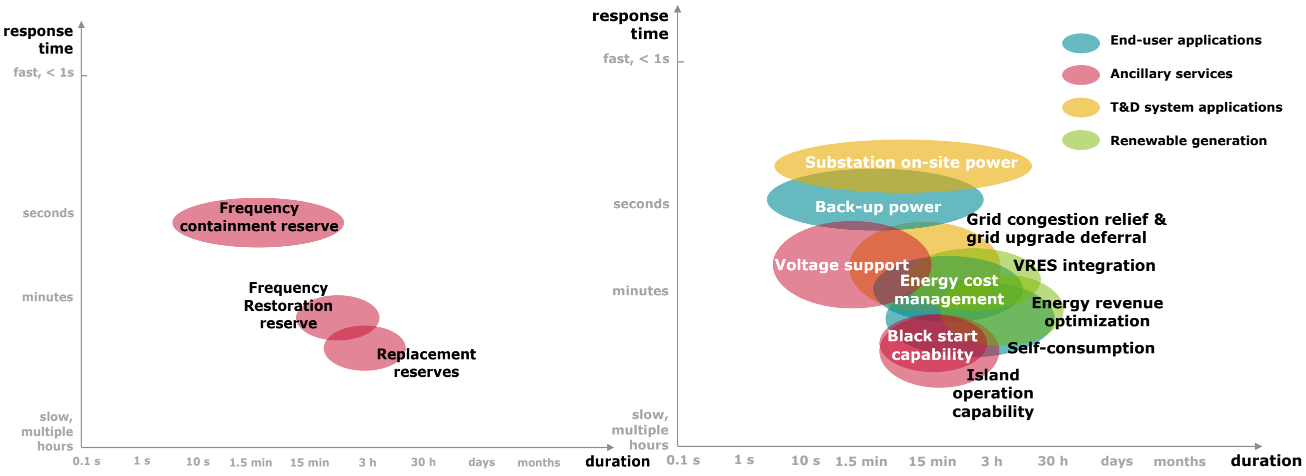
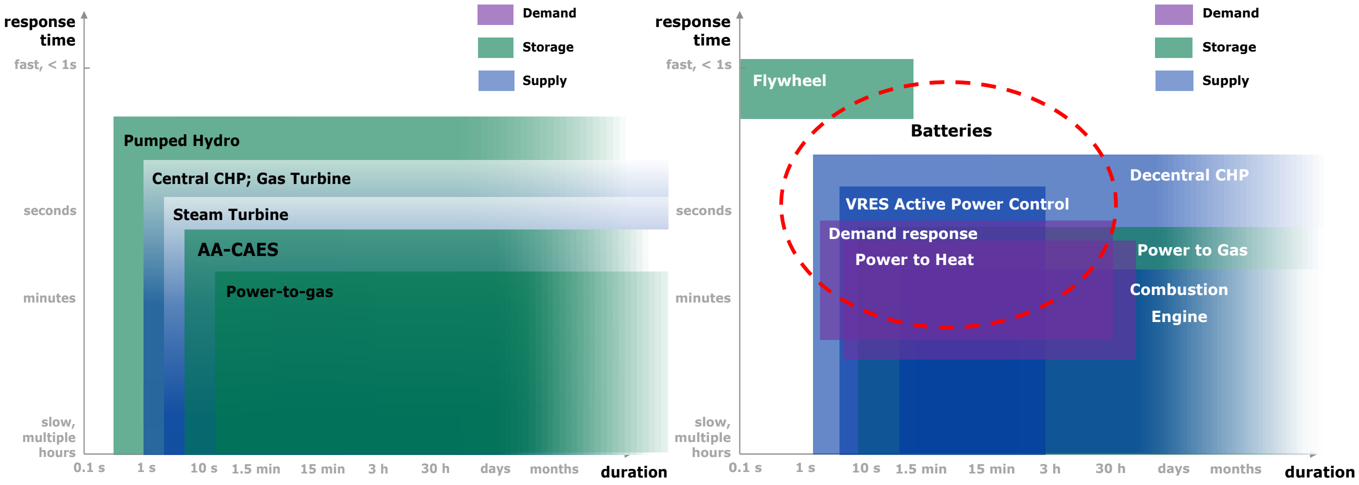


Figure 29: Requirements for response time and duration for central (left) and decentral (right) flexibility applications

Figure 30: Response time and duration of central (left) and decentral (right) flexibility options



The comparison of the figures allows a first assessment of the suitability of the flexibility options for the various applications. The area of an application shown in Figure 29 shows the minimum response time and minimum duration needed to provide the service. Flexibility options need to have a response time equal to or lower than the minimum requirement. Moreover, they need a duration equal to or higher than the minimum requirement depicted inFigure 29. A first mapping of the applications in Figure 29 with the flexibility options in Figure 30 under consideration of the locational needs (i.e. decentral availability needs) shows which flexibility options are generally suitable for which application.

Followed by the first assessment based on the figures above, the degree of suitability of the flexibility options is further analysed in the following section, in which we also including other relevant factors. The suitability of the flexibility options is analysed for each of the applications defined in section 2.1.3. The analysis is done separately for the four application groups: end-user applications, ancillary service applications, transmission and distribution (T&D) system applications and renewable energy applications.

5.2.1 End-user applications

Three end-user applications have been identified in section 2.1.3: self-consumption, energy cost management and back-up power. All three applications refer to the operation of local, on-site available flexibility options. This covers residential, commercial and industrial consumers. Hence, only decentral, on-site available flexibility options are suitable for end-user applications. Central power and storage plants are no options. This includes the group of steam turbines, gas turbines, central CHP, pumped hydro storage and AA-CAES.

The **self-consumption** rate from solar PV depends on the PV generation and consumer demand pattern. As the consumption of the self-generated electricity from the PV system should be maximised, other supply that only decreases the electricity consumption from the grid but does not affect consumption of PV electricity is not suitable. Demand response measures can be suitable to increase self-consumption. With demand response, the consumption can be shifted to match the fluctuating PV electricity generation pattern. The flexibility potential of demand response is dependent on the available household/commercial appliances or industrial processes. Power-to-X options could possibly be suited for this application, however, due to low roundtrip efficiencies if converted back to electricity an investment would currently only make sense for commercial applications that could make use of the hydrogen produced in hours with peak production. Power-to-heat can be an option to increase demand when solar energy is available. The thermal heat storage allows to de-couple the heat demand from the electricity supply.
In contrast to the alternatives mentioned above, battery storage systems have a higher level of flexibility as they affect both demand and supply. They can store the energy in high generation times and the electricity can be used in low generation times when demand is high. Moreover, battery storage systems can usually react faster to short-term generation fluctuations due to fluctuating solar radiation whereas demand response is restricted by the requirements of the flexible electricity loads. Compared to power-to-gas, the roundtrip efficiency of batteries is much higher.

Battery storage systems can be used for **energy cost management**. If variable electricity prices apply, electricity costs can be reduced by shifting demand to times of low prices. Moreover, self-generation can reduce the dependency on retail prices. As retail prices usually vary every 15 minutes, all decentral flexibility options fulfil the low response time requirements. Energy costs can also be reduced by lowering peak demand if the retail price contains a power component.
Demand response is best suited for energy cost management, in particular demand shifting from high to low price periods and/or to reduce peak demand, depending on the energy contract. All controllable decentral generation technologies (CHP, ICE) can further reduce the dependency on retail prices and are well suited if the investment has a positive business case. They can also reduce the peak demand from the grid. Power-to-heat combined with thermal storage can be used for heat generation in times of low electricity prices and lowering demand (by generating less heat) in case of high electricity prices. Heat pumps are most suited if electricity demand for heating is a large part of the overall demand.
Compared to batteries, the shifting of demand in time equals the effects of storing electricity and using it at a later point in time while the potential for demand response is dependent on the household appliances or industrial processes. A combination of decentral self-generation with flexible demand

options (power-to-X) can also adapt demand and supply as batteries can do. The downside of reducing retail price dependency with self-generation is the increased dependency on fuel prices.

In case of a grid failure, end-users rely on **back-up power** to guarantee non-interrupted electricity supply. Back-up power is particularly important for consumers with a continuous electricity demand which cannot be shifted in time, e.g. industrial processes or emergency power for hospitals. A fast response time of seconds to a minute maximum needs to be fulfilled.
Controllable decentral generation technologies are suited for applications which do accept longer response times of about a minute. Flywheels, which have a fast response time but only a limited duration, are only suited for short grid outages or in combination with back-up technologies with a longer duration for processes which do rely on a continuous supply and require a very fast response time. Demand response and power-to-heat are not suitable as these only affect demand.
Batteries, in contrast, have the advantage that they have a fast response time and can provide back-up power for several hours. However, if a longer back-up supply is needed, batteries should be used in combination with decentral generation technologies.

5.2.2 Ancillary service applications

The requirements for flexibility options to provide ancillary service are diverse. Some require decentral solutions while for others central technologies are of advantage. The response time can vary between very fast to several minutes. The following assessment identifies the requirements of each application and matches it to possible flexibility solutions.

Static **voltage stability** (reactive power management) primarily requires a locally evened reactive power balance and therefore the reactive power demand of a grid section must be supplied by local points of feed-in. Decreasing shares of conventional power plants lead to a local deficit of traditional reactive power sources on the transmission grid level. Therefore new options that can perform this specific requirements are needed. As one new option the reactive power provision from new inverter designs of decentralised generation systems can be considered. For the transmission grid a modification of disused power plants for phase shift operation or equipping new power plants for decoupled phase shift operation and building standalone phase shifters are possible. However, these come with high costs.
Additionally to the assessed flexibility options, other technical options are suitable to provide voltage support. Power compensators (inductors, capacitors) and inverter stations of the planned high voltage direct current (HVDC) transmission lines are good examples of new technical solutions to solve this challenge.
Regarding their ability to provide voltage support, batteries may be assessed similarly to VRES, as their power electronics for grid integration works analogically. Through the converter, reactive power and short circuit power can be provided to the grid.

With decreasing shares of traditional providers – central conventional power plants - of **frequency containment reserve (FCR)**, new alternatives are needed which have a fast response time and can ensure to provide fast up- and down-regulation (depending on market rules) for a defined time frame. Frequency containment reserve by VRES or demand solutions are the most cost effective solutions as no new assets need to be built. However as in most countries the FCR products include both – up and

– down regulation, the market conditions would need an additional adaptation. Another disadvantage of VRES and demand options is that both options can only guarantee the availability at all times if a large set of capacity is aggregated. CHP, combustion engines, large central storage and power-to-gas can also provide containment reserves. Decentral providers should be aggregated to one virtual system to ensure availability and to meet the volume requirements of the balancing market.
Batteries are very well-suited for this role, as they have a short response time and can offer power fast in both directions.

In comparison to frequency containment reserves, slower response times are required for **frequency restoration reserves** and **replacement reserves**. Therefore today these services are provided by conventional power plants and pumped hydro. However, with decreasing full-load hours of conventional power plants in the future, a rising share of restoration and replacement reserves will be provided by pumped hydro. During hours of low residual load, they can prevent curtailing or the export of VRES and they allow for the operation of base load power plants, in particular during the midday PV production peak. Therefore steam turbines and VRES (mostly negative balancing direction) which are also well-suited as frequency restoration reserves, can be used in combination. With very high negative balancing needs also the less efficient storage technologies power to gas and AA-CAES can play a role. With innovations in the communication technology decentral technologies can be aggregated to provide restoration and replacement reserves. Active research is ongoing aggregating decentral residential batteries to provide negative restoration and replacement reserves. For larger battery systems the storage capacity, which is the main cost driver, limits batteries' capability as frequency restoration reserve or replacement reserve.

Large-scale pumped-hydro storage and gas turbines are current examples of **black start** capable power plants, which can be started with batteries or emergency power systems even in the event of a blackout [Dena 2014]. Their advantage is that they can produce energy for the required duration and can meet strict requirements on synchronization, resilience, and other controls. However, with the increasing political will to replace those solutions with low carbon technologies, new options also in the distribution grid are needed. The fluctuating nature and higher control needs of VRES make them less-suited for black start.
A (virtual) connection to large storage systems could increase their availability and therefore their suitability. Being able to control the demand to restart the grid in a distributed fashion is a further step to new solutions for black starts.

5.2.3 Transmission and distribution (T&D) system applications

Three applications have been identified in section 2.1.3 for T&D system applications: grid congestion relief, grid upgrade deferral and substation on-site power. For all of the identified applications the location of the solution in the distribution or transmission grid is highly relevant. Investments in grid upgrade (e.g. investing in a new transformer) can be seen as natural competition but will not be analysed in this flexibility options assessment.

In order to relieve decentral **grid congestion** the flexibility options should be a decentral solution with down-regulating capability and short to medium response times close to the peak load in a certain grid area. The required size (MW) depends on its deployment in either the transmission or the distribution grid. For the transmission level the down regulation of conventional power plants is the best suited flexibility option to relief congestions.

In the distribution grid the curtailment of distributed generation can reduce peaks at low costs. Additionally power-to-X technologies can be suited to relief congestions but their applicability is limited to the heat or hydrogen demand.

Batteries are an excellent choice to relieve congestion problems at the distribution system level. Energy would be stored when there is no congestion, and it would be discharged (during peak demand periods) to reduce distribution capacity requirements.

The most relevant factor to **grid upgrade deferral** is the location of the overloaded node on the transmission or distribution level. By using energy storage, utilities investments in T&D upgrades can be delayed in time – and in some cases avoided entirely. Curtailing VRES or other decentral generation is the lowest cost option to reduce peaks while being able to install more capacity and reduce the needs of grid upgrades at the same time. Power-to-X technologies are well suited to defer distribution upgrades by reducing peak feed-in of decentral generation. For the same reason pumped hydro and AA-CAES are suited to defer transmission upgrades. However, the deployment of these options is limited to the location, which might not coincide with the location of the overloaded node in the electricity grid.

Batteries offer a significant advantage here as these can be deployed almost anywhere. An additional advantage is their modularity. Therefore, they can be adopted to changing grid needs quickly [RMI 2015].

Substation On-Site Power requires fast response up-regulation in case of grid failure, located decentral close to the substation. Combustion engines are therefore a good choice to provide on-site power over a longer duration. Also CHP can provide energy to substations however only if the heat output can be used this is a potential business case.

Batteries fulfil the criteria of fast response time and can be scaled in order to serve specific grid needs decentral. However, the duration needs of on-site power vary for this application between seconds and hours. For large duration needs a large storage capacity is needed which highly increases costs.

5.2.4 Renewable energy applications

RES applications are partly linked to the location of the flexibility. Energy revenue optimisation can be done within the balancing group where location is usually not considered a relevant factor (depending on regulation). In contrast, VRES integration is dependent on the regional availability of flexibility.

Energy revenue optimisation refers to the value of VRES. Battery storage can be used in conjunction with VRES to optimise the income from VRES. This includes arbitrage opportunities and the optimisation of the schedule of the balancing group including VRES to reduce balancing energy costs.

Storage systems are the preferred option for revenue optimisation as storing electricity offers the largest flexibility in shifting non-controllable generation in time. Pumped hydro, AA-CAES and power-to-gas are well suited. Low efficiency rates (e.g. of power-to-gas systems) decrease revenues. Active power control of VRES can also be used to reduce deviations from the schedule, e.g. by curtailing wind and PV production, however this comes with the costs of "wasting" renewable energy generation.

Decentral controllable generation is also less suited, as it does not affect the VRES in-feed itself but can be used to balance demand and (VRES) supply inside the balancing group.
Battery storage systems have lower durations than pumped storage and power-to-gas but can reach similar durations as AA-CAES. Capacities are still large enough for balancing schedules. The batteries' suitability for arbitrage opportunities is dependent on the energy revenue optimisation strategy. Batteries are the preferred option for short-term arbitrage whereas storage systems with larger durations are best suited for long-term, seasonal arbitrage strategies.

Energy storage can be used to support **VRES integration** by optimising the output of VRES to increase supply quality and value. Relevant characteristics of VRES that define quality and value are ramping and fluctuations in time. VRES integration can be improved by providing flexibility options that help to reduce VRES curtailment due to congestion management in the distribution or transmission grid. To overcome local congestions, flexibility options must be decentral available.
Power-to-gas can deal with local and system level congestions and is thus a preferred flexibility option for VRES integration. Large, central storage systems are also well suited. Due to central availability they can only act on system level but have higher efficiency rates. Electricity supply options can be used for local or system balancing. For these, the relevant factors for VRES integration are location, response time, heat demand dependency of CHP limits, the potential and suitability. VRES active power control is an option to deploy higher VRES capacities within a grid with limited capacity but reduces the value of VRES.
In summary, batteries are the preferred option to enable VRES integration, due to their decentral applicability, high efficiency rates and fast response times they can optimally support VRES integration.

5.3 Summary competition technology assessment

The following table shows the ranking of flexibility options that includes both technical and economic parameters and compares the described technologies with central and decentral battery storage systems.

In a first step technologies which are technically not suited to provide a certain type of flexibility have been excluded. This assessment is based on the results of chapter 5.2. Reasons why a certain technology is not suited to provide flexibility for a certain application could be that one or more of the following requirements are not met:

- Response time;
- Energy content (duration);
- Power ratings;
- Power gradients;
- Ability to increase and decrease power infeed (bi-directional).

For each application we then assessed if the remaining flexibility options can provide an overall economic benefit if added to the system. This assessment was based on the merit-order approach by [FfE 2016]. In this study different flexibility options have been ranked on their economic advantage to the overall electricity system and matched to the demand of this flexibility application. A matching between the applications introduced in section 2.1.3 and the applications used in the FfE study can be found in Appendix D: Applications FfE – BATSTORM. Technologies that are cheaper than the currently used options to provide flexibility within the given applications will lead to a system cost reduction and are marked in green. If a technology only leads to cost reduction in specific parts of the system, it is marked in yellow. Options that are technically suited for a certain application but lead to additional costs if installed, are marked red. As this assessment takes the current energy system with technologies as used today as the reference scenario, conventional generation has been excluded from the table. The remaining flexibility options can be grouped in supply, demand and storage. Flexibility can either be added to the system with new installations such as power-to-gas or flywheels or by ‘flexibilising’ (and aggregating) demand or production.

Central and decentral battery systems were compared to the competing flexibility technologies as part of the merit-order approach. For most applications the system costs of lithium-ion batteries were used. Only for applications were lead-acid is predominant (substation on-site power, back-up power) the lead-acid prices were used. Central battery systems describe batteries with a capacity of several MWh and is usually placed in front of the meter, while decentral systems are systems with a capacity of several kWh and connected to residential or commercial customers. These decentral systems need aggregation in order to provide flexibility within most applications.

As shown in Table 6 only few technology options would lead to a system cost reduction in the current energy system. Conventional generation is still the cheapest option to provide flexibility in most cases. However, when the share of renewables increases over time this picture will change and additional flexibility options are needed.

The flexibilisation of demand, curtailment and aggregating decentral generation lead to system cost reductions already today. However, curtailment reduces the share of renewable energies and decentral generation uses fossil fuels. Therefore, even if cost effective, from the environmental point of view other options that allow higher shares of renewable energies are preferred.

Battery storage is technically suited to provide flexibility in all applications. However, only for frequency containment reserve, island operation and substation on-site power the installation of a battery leads to reduced system costs already today. The high potential also compared to other flexibility options is seen when looking at the applications where batteries can already lead to a partial system cost reduction when compared to other flexibility options and the status-quo. In almost every application, batteries have a competitive advantage restricted to specific countries (depending on regulatory framework, network prices and electricity price design) or grid regions (high curtailment, blackouts, unstable grids).

Table 6: Technical suitability and economic advantage of competing technologies providing flexibility to the system in relevant applications; Source: own representation based on [FfE 2016]

Application		Supply			Demand		Storage					
		Decentral CHP	Combustion engine	VRES Active Power Control	Demand response	Power to Heat	Pumped hydro storage	AA-CAES	Flywheels	Power to Gas	Central battery	Decentral battery
End-user applications	Self-Consumption	☒	☒	☒	🟢	🟠	☒	☒	☒	☒	🟠	🟠
	Energy Cost Management	☒	☒	☒	🟢	🟠	☒	☒	☒	🔴	🟠	🟠
	Backup Power	🟠	🟠	☒	☒	☒	☒	☒	🟠	☒	🟠	🟠
Ancillary services	Voltage Support[28]	🟠	🟠	🟠	☒	☒	🟢	🔴	☒	🔴	🔴	🔴
	Frequency Containment Reserves	🟠	🟠	☒	☒	☒	🟠	🟠	☒	☒	🟢	🟠
	Frequency Restoration Reserve	☒	☒	☒	🟠	🟠	🔴	🔴	☒	🔴	🟠	🟠
	Replacement Reserves	☒	☒	☒	🟠	🟠	🔴	🔴	☒	🔴	🔴	🔴
	Black start capability	🟢	🟢	☒	☒	☒	🟠	🔴	☒	🔴	🟠	🟠
	Island operation capability	🟢	🟢	☒	☒	☒	🟠	🔴	☒	🔴	🟢	🟠
T&D System Applications	Grid Congestion Relief[44]	🟠	🟠	🟠	🟢	🟠	☒	☒	☒	☒	🟠	🟠
	Grid Upgrade Deferral	🟠	🟠	🔴	🟠	🟠	☒	☒	☒	☒	🟠	🟠
	Substation On-Site Power	🟠	🟠	☒	☒	☒	☒	☒	☒	☒	🟢	🟢
Renewable generation Applications	Energy Revenues Optimization	🟠	🟠	🟠	🟠	🟠	🟠	🔴	🔴	🔴	🔴	🔴
	VRES integration	🟠	🟠	🟢	🟢	🟢	🟠	🔴	🔴	🔴	🟠	🟠

🟢 System cost reduction / 🟠 Partial system cost reduction / 🔴 No cost reduction ☒ no technical suitability

---

[28] Large scale systems can provide voltage support and grid congestion relief on transmission system level while distributed systems provide those services on distribution system level.

6 Battery capacity development scenarios

A preliminary outlook for battery capacity development up to 2020 and 2025/2030 is discussed in this chapter, building on existing analyses. Firstly (in section 6.1), the overall role of electrical energy storage (including but not limited to batteries) in scenario's for the German and European energy system is discussed. However, most of these studies focus on the role of large scale storage of electrical energy at a transmission grid level, without considering the other applications (such as distribution grid congestion or behind the meter at users). Secondly (in section 6.2), the specific outlook for batteries in a range of applications is considered taking the current installed capacity as a starting point, while considering the expected growth in key drivers for these applications for the timeframe up to 2030.

This is a preliminary development scenario that is to be further developed in the following 12 months of this study, as more information will be gathered on the growth potential as well as for specific drivers and hurdles.

6.1 Meta-review of capacity development scenarios for energy storage

This section provides an overview of available information on the future need of storage capacity, based on existing studies. The results reported below were predominantly extracted from the German study "Metastudie Energiespeicher" [29] which mainly focuses on the German power system [Fraunhofer UMSICHT, Fraunhofer IWES 2014].

Regarding the future energy system in Europe, various different assumptions were made, and the methodology used varied significantly. Systematic influences from the assumed power consumption, peak load, and so called must-run units were found in the different scenarios of the studies. Interpretation and comparing of results must thus be done with caution.

The considered studies were divided in groups representing different approaches to analyse the future energy system:

- **European power supply at minimum costs:** The bulk of studies in this group analysed the allocation of RES capacities and the investment in grid infrastructure in a cost minimizing linear program or other kinds of algorithms without constraints regarding current developments and planned infrastructure. Therefore, these studies predominantly focused on the year 2050 or a scenario with 100% energy supply from RES: [Schabram et al 2013, SRU 2011, Fraunhofer ISI 2011, Dena, IAEW 2012, Bussar et al. 2014, Droste-Franke 2012, Czisch 2005, EWI, energynautics 2011, Fraunhofer IWES, et al. 2014, Pleßmann et al. 2014];
- **Development of the German power system in Europe:** Most of these studies considered the quantitative aim of developing RES and the progress of developing the grid infrastructure. They mostly assumed a full grid development according to the current Ten Year Network Development Plan (TYNDP) of the European TSOs [ENTSO-E 2015a] and the domestic planning of the German TSOs. From this basis the need of additional plants and storage

---

[29] Funded by the Federal Ministry of Economy and Energy, Germany.

capacity was calculated in a cost minimizing optimization considering the current conventional plants and their lifetime. These studies focused mostly on the period up to 2020 and 2030, while a few studies considered 2050 too: [CONSENTEC, Fraunhofer IWES 2013, BET 2011, EWI 2012, EWI 2013, IER 2010, IER, et al. 2010, Jentsch, et al. 2014, Prognos 2011, 50Hertz Transmission GmbH et al. 2013, Prognos, et al. 2011, DLR et al. 2012, CONSENTEC, IAEW 2011, EWI, energynautics 2011, dena, IAEW 2012, Agora 2014, Fraunhofer IWES, et al. 2014, EWI, EEFA 2008, IAEW 2013, Frontier economics, swissQuant 2013, ZSW 2014]. Furthermore, some studies consider a delayed development of the grid or even compare both scenarios: [CONSENTEC, Fraunhofer IWES 2013, EWI 2013, CONSENTEC, r2b energy consulting 2010, EWI, energynautics 2011, Fraunhofer IWES, et al. 2014];

- Results from **further studies focusing on the German power system** were only considered in [Fraunhofer UMSICHT, Fraunhofer IWES 2014]. Data from those studies are contained in the figures below. However, results were not discussed in this summary: [VDE 2012, Fraunhofer UMSICHT, Fraunhofer IOSB/AST 2013, TAB 2012, Genoese, Genoese 2014, Planet GbR, et al. 2014, UBA 2010, SRU 2011, Fraunhofer ISE 2012].

Even within these groups the results varied strongly as the model of the European power system, the assumptions and the applied data included considerable variation. The methodology, which in most cases is a linear program (LP) or a mixed-integer linear program (MILP), is implemented respecting a trade-off between the model accuracy and the run time of solving the LP or MILP by state-of-the-art software. Therefore, variations usually not considered in these studies are, for example, sizing the capacity of different decentralized storage technologies, acquiring the potential of demand side management, and employing all these capacities in various business cases and domestic control reserve markets in Europe. Future power plants and storages either were defined exogenously in the LP/MILP, or they have been a result from endogenously modelling the need of capacity.

Two aspects can be extracted from most of these studies which give an indication on the need for storage capacity, but which should be treated with caution. Firstly, the need of additional power plants and storage capacity, and secondly, a surplus of generated power from RES that must be curtailed because either there is not enough demand in the considered system or the power cannot be distributed to a consumer due to grid bottlenecks. The reason to be cautious is that surplus power is either allowed or stored, while disregarding the economic feasibility of storage due to different requirements set in a study. Furthermore, the results of the needed capacity and the employed technology are highly sensitive with respect to the assumed costs and the allowed solutions. For example, recent studies frequently consider electrochemical storage, flexible biogas and CHP plants, and demand side flexibility. Furthermore, studies about the German power system in Europe often incorporate the disputed constraint that the peak demand has to be covered by domestic capacities. The results of different studies have shown that a European power system without cross-border constraints reduces the need for generation capacity to complement wind and solar power in Germany in 2050. It can be assumed that these results apply to most of the European countries. The figure below shows the generation capacity in the Germany power system if wind and solar power are omitted.

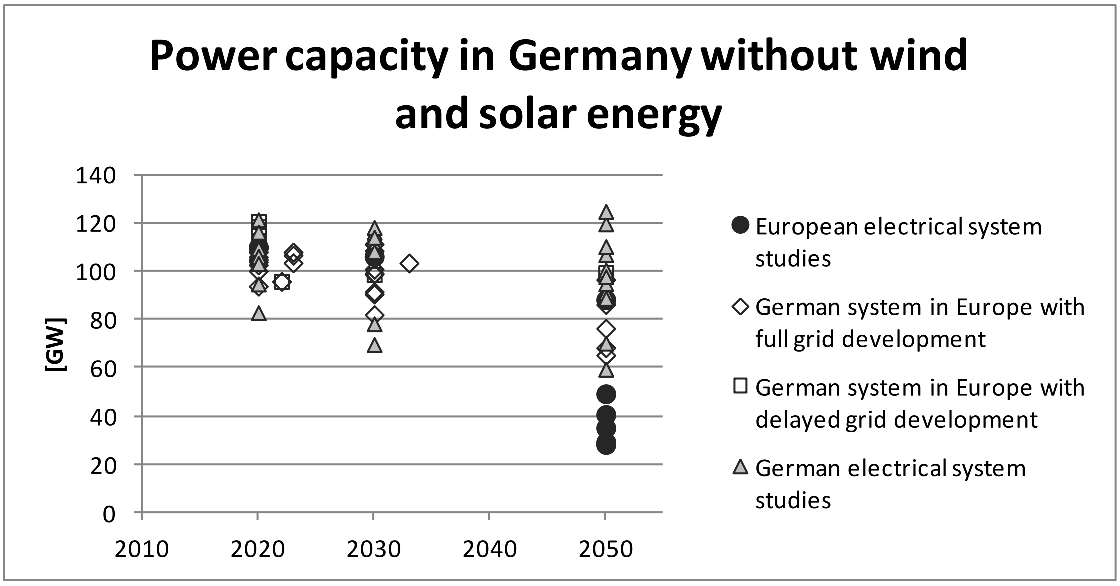


Figure 31: Total capacity of power plants in Germany without wind and solar power [Fraunhofer UMSICHT, Fraunhofer IWES 2014]

6.1.1 The need of generation and storage capacity in Germany

To maintain the required total capacity, new generation and storage capacity is needed. Besides the generation plants planned and constructed by now, new capacity is needed to cover peak demand. There are two approaches to define the need of additional capacity. The first approach defines capacity exogenously by analysing the residual load and the capacity of plants that will be decommissioned. An alternative approach calculates the capacity endogenously in an optimization resulting in the lowest cost solution for the considered system. However, policy constraints concerning the capacity of domestic plants may influence both approaches. The resulting need of capacity per technology is shown in Figure 32 and Figure 33 forecasted in 2020 and 2030, respectively.

The figures show that the results about the need for additional capacity varied within a wide range: between 3 GW and 45 GW in 2020 and between 14 GW and 52 GW in 2030. Most of the additional capacity identified is needed due to the integration of fluctuating wind and solar power generation. Only a few studies resulted in a need for a small amount of capacity of base load plants. Some studies resulted in a need of storage capacity. Technologies considered for storage were mostly pumped hydro storage (PHS) and compressed air energy storages (CAES). Thus, battery based storage was not specifically considered. This is due to the assumptions on storage technology costs on the one hand and the authors not being aware of business cases on the distribution level on the other hand. Furthermore, there is a dispute on the assumptions as it is not clear whether storage can be regarded as reliable capacity.

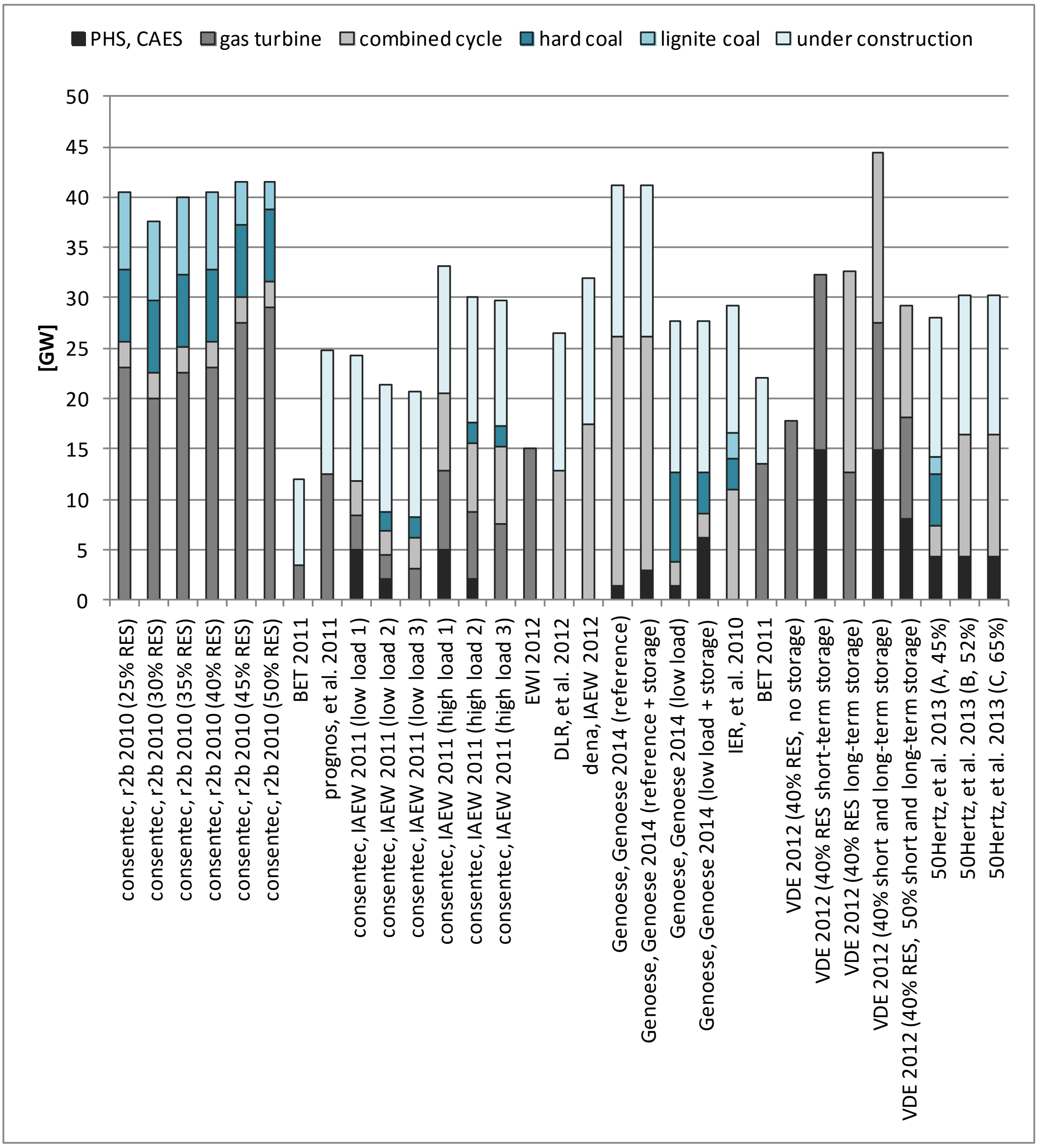


Figure 32: Additional plant and storage capacity needed in Germany in the short-term scenario (2020-2023) [Fraunhofer UMSICHT, Fraunhofer IWES 2014]

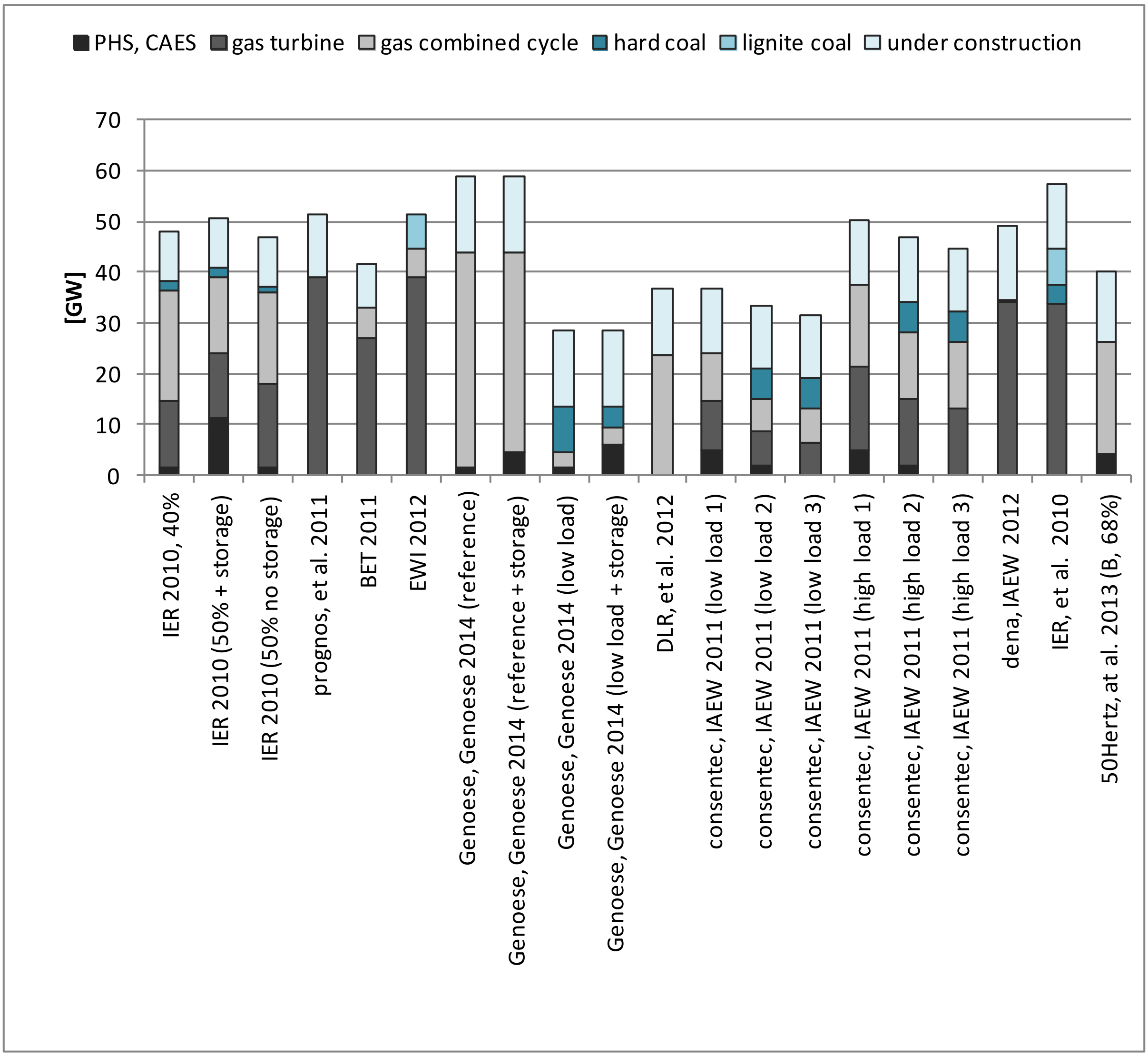


Figure 33: Additional plant and storage capacity needed in Germany in the long-term scenario (2030-2032) Fraunhofer UMSICHT, Fraunhofer IWES 2014]

Remarkable results have been obtained by [Agora 2014, Fraunhofer IWES et al. 2014, VDE 2012]. They have defined storage exogenously in the future scenario, analysing the system's cost savings. The results indicated that an economical advantage can hardly be obtained by additional storage capacity (see Figure 34 and Figure 35). The overall savings, indicated in blue, are always negative and thus leading to negative economic effects. Some values vary according to the flexibility of the scenarios. There are some significant savings in the grid or regarding curtailment of RES but the cost of the storage technologies outweigh the benefits. Only one study shows small positive economic effect in 2030.

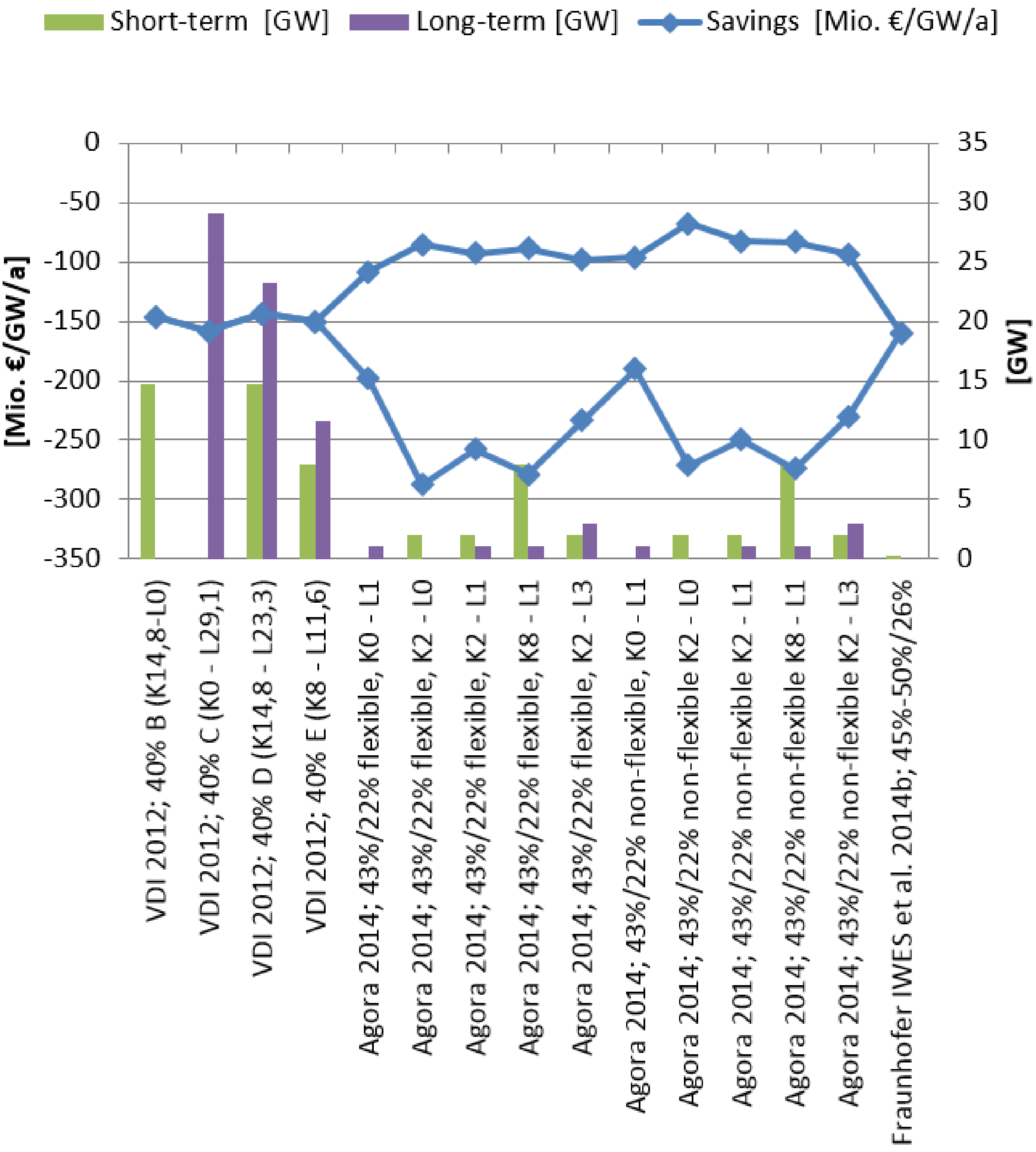


Figure 34: Over-all savings in short-term scenarios (2020-2023). [Agora 2014, Fraunhofer IWES et al. 2014, VDE 2012]

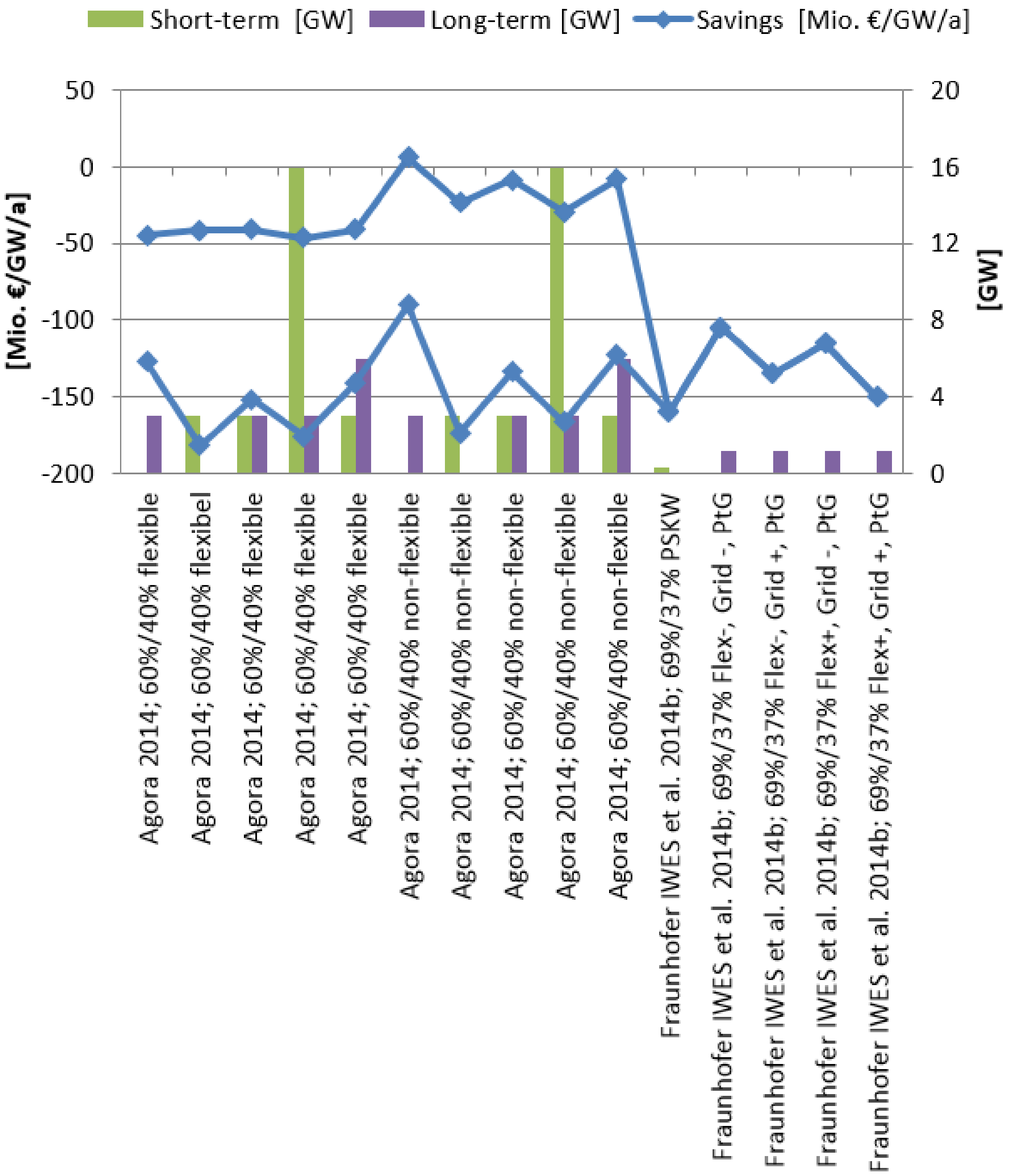


Figure 35: Over-all savings in long-term scenarios (2030-2033). [Agora 2014, Fraunhofer IWES et al. 2014, VDE 2012]

For the year 2050 or a 100% power supply from RES, the capacities needed in addition to wind and solar energy in Germany are shown in Figure 36. The assumed power generation from RES and the net import to Germany are illustrated too. The total plant and storage capacity varied over a wide range between 30 GW and 120 GW. The result of total storage capacity varied between 8 GW, which represents the capacity of pumped hydro storages in Germany today, and 43 GW, which was defined exogenously. Much studies forecasted predominantly gas turbines and combined cycle gas turbines to cover the capacity required in the German power system. These plants may be operated by natural gas and synthetic gas obtained from electrolysis and methane synthesis (which could be tied to their role in long-term energy storage). However, the results varied strongly depending on the modelling approach and the underlying assumptions. For example, [SRU 2011] presented a technology mix with large integration of compressed air energy storage technology, resulting in a minimum of surplus energy from optimizing both the German power system only and the European power system. In contrast, [UBA 2010] first defined a reasonable mix of RES in Germany to cover the energy demand, while determining electrolysis capacity in a second step to store the surplus power generation.

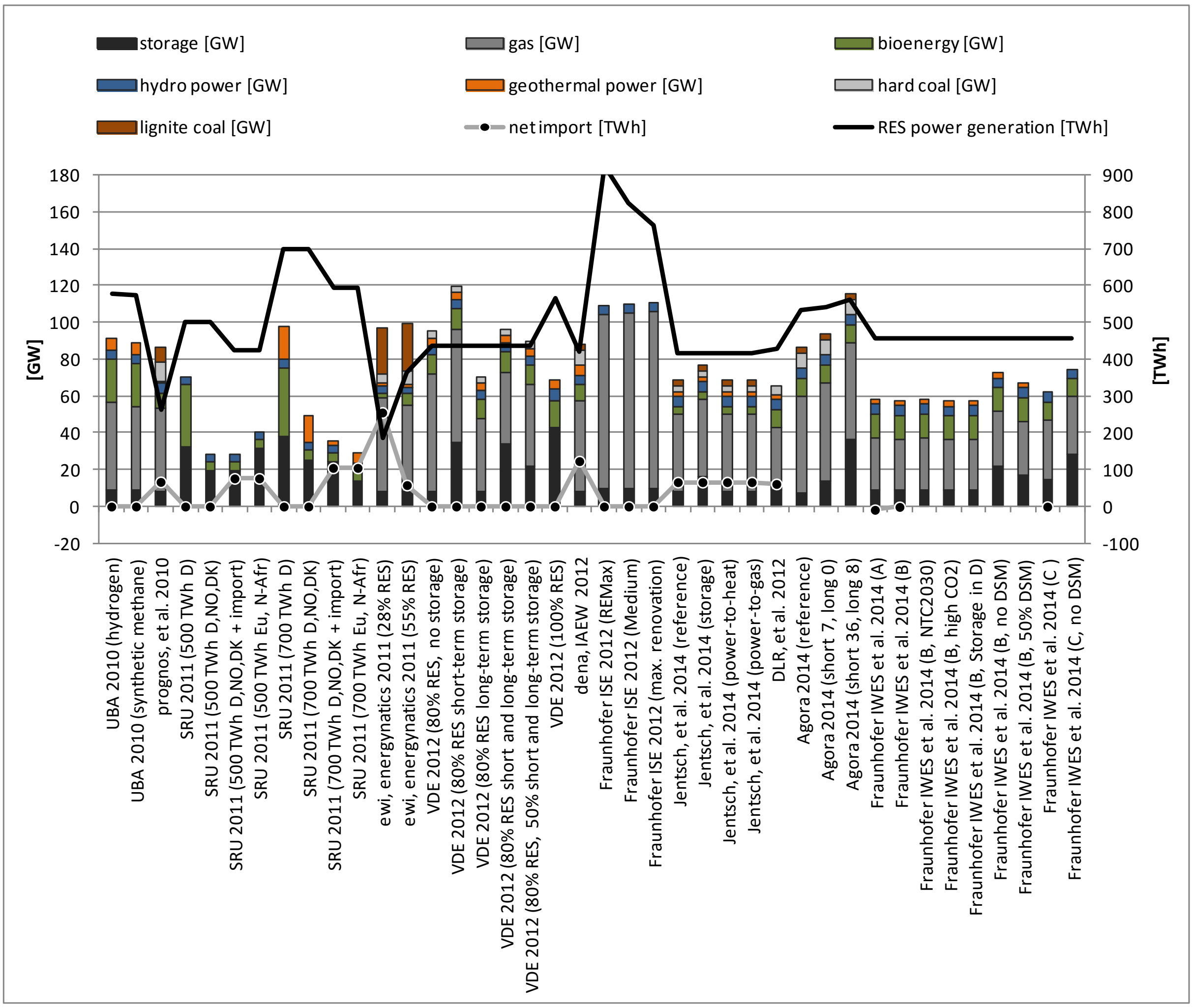


Figure 36: Total plant and storage capacity needed in Germany in 2050, except for wind and solar energy [Fraunhofer UMSICHT, Fraunhofer IWES 2014]

6.1.2 The surplus of RES power generation in Germany

Figure 37 illustrates the surplus power generation and the entire power generation from RES in Germany based on the studies that also considered the European power system. The surplus energy did not vary depending on the assumed share of RES in Germany but on the assumption as discussed above. A much more significant relationship can be derived from Figure 38 and Figure 39. These illustrate that a lot of studies found a significant surplus of power generation in Germany, with an increasing range depending on the growing share of RES. The most significant results were obtained from studies focusing on the impact of the German energy transition embedded in the European power system. Analysing 2020, 2022 and 2023, while expecting a delay of planned grid expansion, the surplus energy was between 2.5 TWh and 15 TWh in most of the studies, even exceeding 30 TWh in one scenario that considered a 50% share of RES.

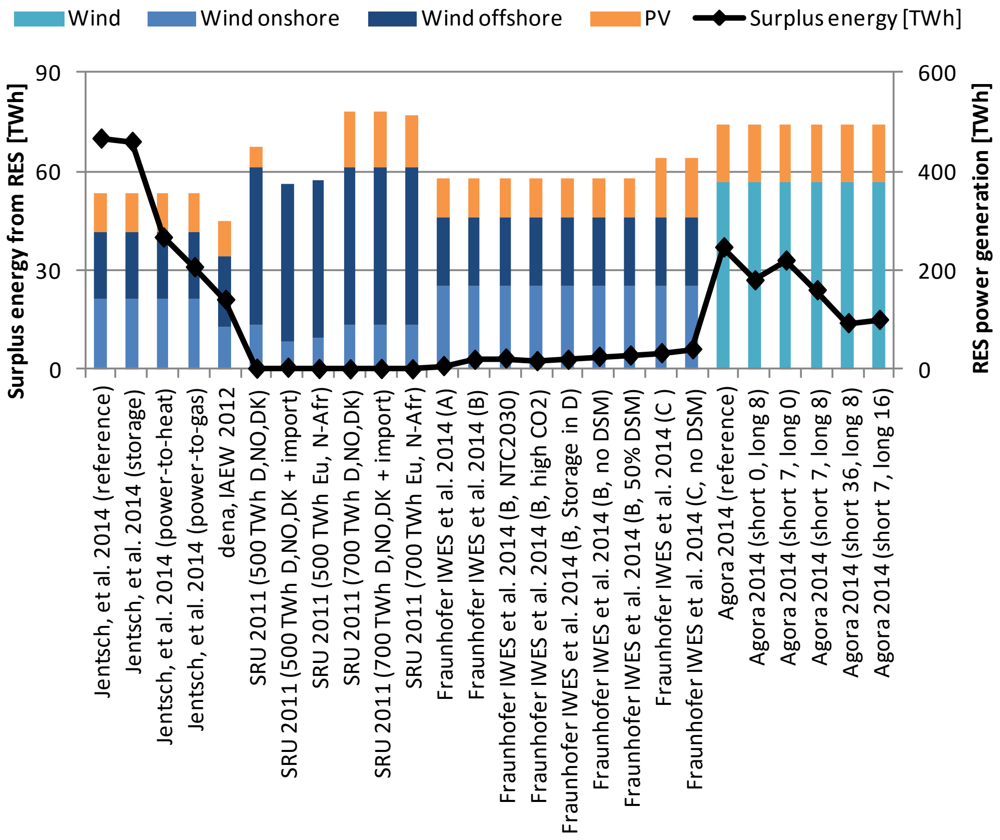


Figure 37: Wind and solar power generation and surplus energy from RES in Germany in 2050 [Fraunhofer UMSICHT, Fraunhofer IWES 2014]

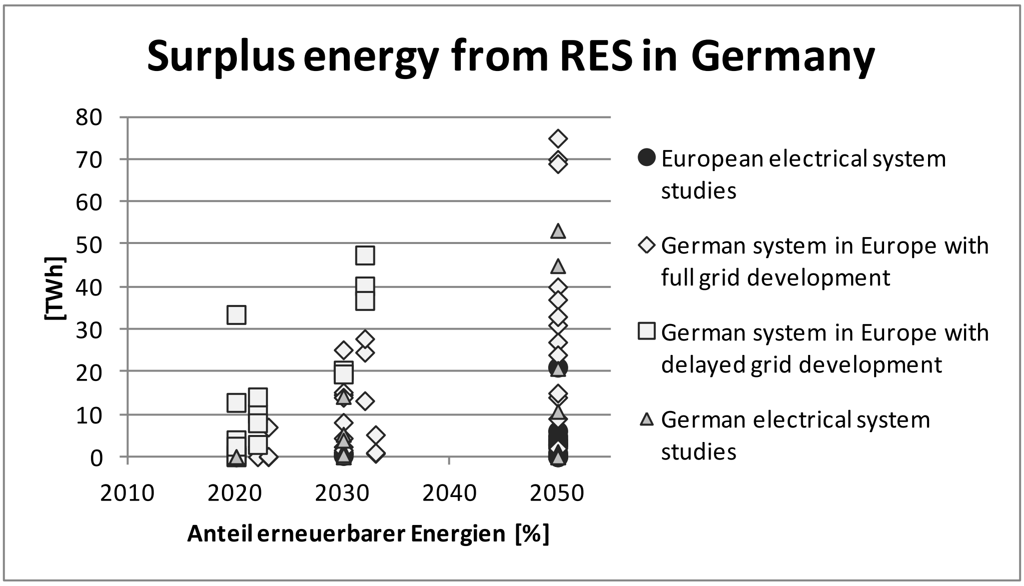


Figure 38: Surplus energy from RES in Germany depending on the year, distinguishing between the approach of the studies [Fraunhofer UMSICHT, Fraunhofer IWES 2014]

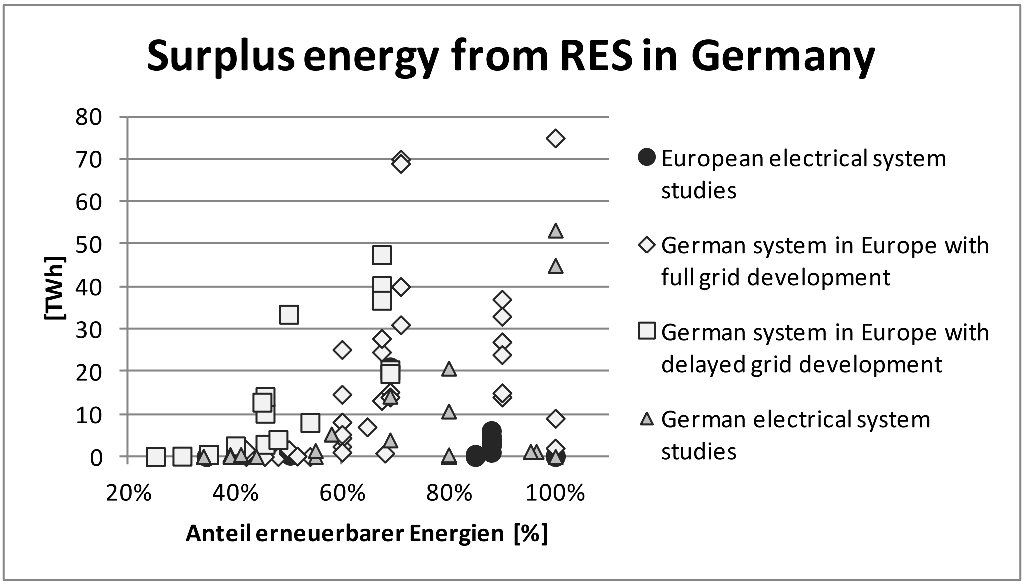


Figure 39: Surplus energy from RES in Germany depending on the share of RES, distinguishing between the approach of the studies [Fraunhofer UMSICHT, Fraunhofer IWES 2014]

6.1.3 Highlighted studies forecasting storage capacity in Europe

[Bussar, et al. 2014] found a need for storage capacity of about 50 GW/300 GWh battery capacity (NaS), 160 GW/2300 GWh pumped hydro storage and 360 GW(charge)/320 GW(discharge)/245000 GWh considering a 100% electricity supply from RES in Europe, Northern Africa and Middle East. Notably battery storage was located in Northern Africa and the Middle East only.

[SRU 2011] calculated four scenarios each with a high and low electricity demand. One scenario considered 100% electricity supply from RES in Europe and Northern Africa. The version of the low electricity demand considered a demand of 5400 TWh in Europe of which 509 TWh in Germany. They found that this scenario needed compressed air energy storage of about 230 GW and 100 GW pumped hydro storage. The second version raised the electricity consumption of Germany to 700 TWh, which raised the need of compressed air energy storage to 330 GW and the need of pumped hydro storage to 138 GW. Both scenarios incorporated a minimum surplus generation of 0.1 TWh and 0.0 TWh, respectively.

[Fraunhofer ISI 2011] found an additional need of storage of 3.3 GW and 5 GW raising the share of RES from 2040 to 2050 considering two scenarios of the European electricity demand, respectively 2600 TWh and 3200 TWh. The total storage capacity including existing storages and storages under construction at EU level was about 47.7 GW and 49.3 GW, respectively. About 3.7% and 4.9% of RES generation was curtailed in the scenario of 2050 and conventional power plants generated about 200 TWh of the electricity demand within both scenarios.

[Fraunhofer IWES, et al. 2014] found a need of electrochemical storage (PbS) between 3.4 GW and 131.3 GW in 2050 and an electrolysis capacity up to 0.8 GW at a 82% share of RES in Europe. They distinguished between three main scenarios, and made further variations. The basic scenario (A) respects the national planning of the EU-members, resulting in 3.4 GW/20.2 GWh battery storage. Substituting a share of the planned concentrated solar power (CSP) plants in Northern Africa by wind energy in Europe in scenario (B) increased the needed battery storage to about 7.8 GW/58.2 GWh. Reducing the assumed potential of demand side management raised the need of battery storage to about 40-60GW/ 170-256 GWh in this scenario. The third scenario (C) substituted completely CSP and geothermal power and a share of the assumed bioenergy by photovoltaic plants. That raised the need of battery storage up to 66 GW/357 GWh, increasing furthermore to 131 GW/619 GWh when disregarding demand side management in this scenario. The study distinguished the endogenously introduced battery capacity in hours expressing the energy relative to the power provided to the system. The findings indicated that a capacity of about 4 hours and 6 hours was needed at most. Disregarding demand side management resulted in an additional need of storages of 2 hour capacity. Figure 40 shows that the resulting need of storage was located mostly in Germany, Great Britain, and Italy, but also in Poland, the Netherlands and Spain (scenario B with respect to DSM). Within scenario C, which is dominated by photovoltaic power generation, respecting DSM resulted in a need of storage located the most in Spain, and Italy, but also in Germany, Great Britain, the Netherlands, Poland, Portugal, Hungary, Ireland, and Slovakia.

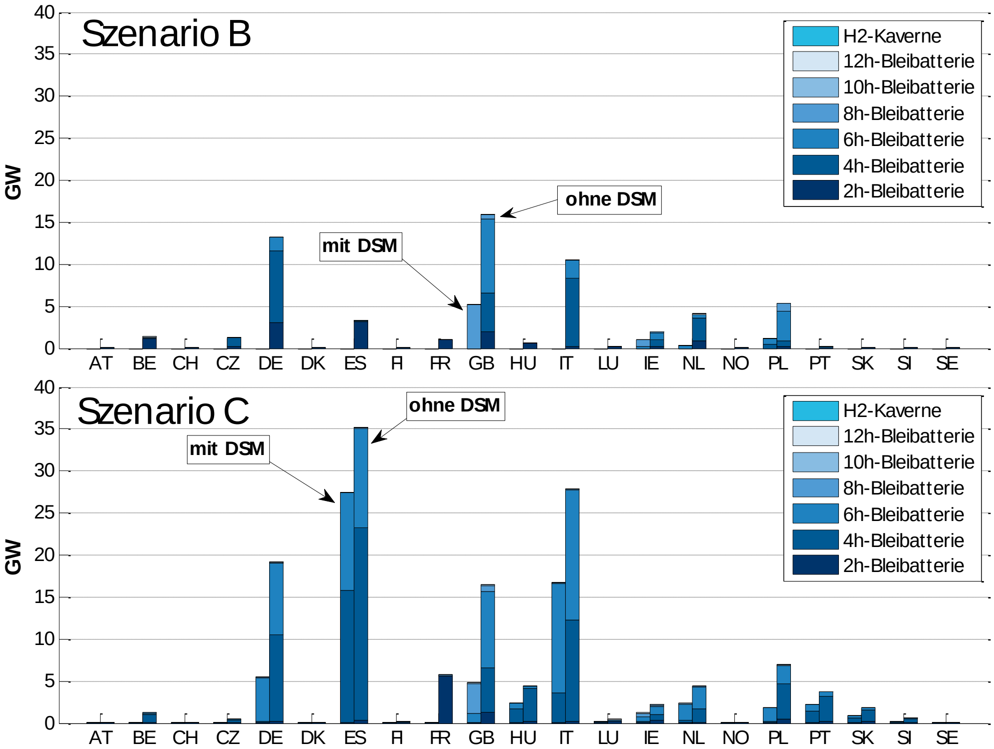


Figure 40: Need of battery storage (PbS) in Europe in scenario B and C, distinguishing between the location, the capacity and the use of demand side management [Fraunhofer IWES, et al. 2014]

6.1.4 Summary scenario's for EU-wide battery storage deployment

In the results in the meta studies, the following scenarios on EU wide battery deployment are presented. Two key points to take into account:

1. As noted before, these studies considered storage needs at the transmission grid balancing level, but did not include other types of applications. These will be considered in more detail in the following section;
2. Both studies consider the 2050 situation, where one should expect that a big part of this need for battery storage materialises with high levels of RES penetration. Therefore, the bigger part of this capacity should be expected in the period 2030-2050, rather than 2015-2030.

Table 7: Overview scenario's for EU-wide battery storage deployment

Source	Timeframe	EU-wide Battery capacity
[Bussar, et al. 2014]	~ 2050 (100% RES system)	50 GW (300 GWh)
[Fraunhofer IWES, et al. 2014]	2050	3 GW to 130 GW

6.2 Potential scenarios for the deployment of batteries in the EU system

The results in section 6.1 had a somewhat narrow focus on storage need for transmission grid balancing, while not considering the demand for and the specific business cases associated with other applications. This section aims at filling this gap. For this purpose we are considering a range of applications and have identified the primary growth drivers that influence the potential demand for battery storage for each of these. Subsequently, the growth of each of these drivers compared to the situation in 2016 is considered. Finally, a first order of magnitude assessment of the potential of battery storage for these application is given.

One important issue to consider when interpreting this analysis is that from other studies [Ecofys 2016] it is clear that there is a significant potential for overlap between multiple applications. That is, some battery systems intended primarily for application A, may also serve a different application B when controlled in a smart way. This is due to the fact that, in many cases this demand for services does not occur at the same point in time. While this theoretical potential may not always be easy to capture as it will require delicate coordination between owners and stakeholders, it could also significantly improve the business case for such battery systems due to the CAPEX-intensive nature of battery systems.

Secondly, it is important to appreciate that for most applications there are competing technologies that - depending on the development of their cost relative to that of batteries – could play an important role in fulfilling part of the demand in the respective application instead of batteries.

At this stage our projection follows a bottom-up approach based on the analyses of all identified fields of application for battery based energy storage. We therefore developed scenarios for each application and combined them to our overall projection for the future deployment of battery systems in 2020 and 2025 in terms of total installed capacity. The specific outlook for batteries in a range of applications is considered taking the current installed capacity as a starting point, while considering the expected growth in key drivers for these applications of the timeframe up to 2025.

In this section we are presenting development scenarios for these applications:

- End-user applications
  - Self-consumption
  - Energy cost management
  - Backup power
- Ancillary services
  - Voltage Support and black start capability
  - Enhanced frequency response
  - Frequency containment reserves
  - Automatic frequency restoration reserve
  - Manual frequency restoration reserve
  - Replacement reserves
  - Island operation capability
- Transmission and distribution system applications
  - Grid congestion relief and grid upgrade deferral
  - Substation on-site power
- Renewable energy sources applications

- Energy revenues optimisation and VRES integration

6.2.1 End-user applications

Self-consumption

The battery application for self-consumption experienced a strong increase over the last couple of years. This development was mainly driven by the German market where PV reached grid parity for new installations around 2012. This made consuming self-produced PV electricity more profitable than feeding the electricity back into the grid to receive a feed-in tariff. [Agora 2014] In this period low interest rates on savings leading to low perceived opportunity costs were the main driver for households to install batteries for self-consumption. Furthermore Germany introduced a promotion programme in 2013 that offers low-interest loans and repayment bonuses for residential PV-connected storage systems,. Additionally, the impact of emotional drivers as autonomy should not be underestimated. Due to these developments the number of residential storage systems increased from approximately 1,000 systems installed by early adopters at the beginning of 2013 to almost 35,000 systems at the end of January 2016 [RWTH 2016]. With a system size of 3 – 4 kW/battery this results in 136 MW of residential storage installed today in Germany alone. With decreasing battery system costs, further increasing electricity prices and the extension of the promotion programme to end of 2018 the German market is expected to maintain the high growth rates of the past three years resulting in an installed capacity of 600 MW in 2020 [Agora 2014]. Around 2021 the feed-in tariff for installed PV systems in Germany will expire, making it unprofitable to feed into the grid. Therefore a further increase of storage installations due to the retrofit of already installed PV panels is expected after this point [Fraunhofer 2015b].

In other European markets residential storage systems are on the edge of profitability and therefore the number of installed systems is still very low, led by only some early adopters. Within Europe Italy, the UK and Belgium are seen as the markets with the highest potential for residential batteries as most residential PV systems are installed in these countries. Together with Germany the four countries account for 80% of the installed residential PV capacity in Europe [EC 2015b]. Removing regulatory barriers such as net-metering in Belgium will accelerate the market penetration.

Italy has the second largest share of residential PV systems installed in Europe but due to restructuring of the support schemes for residential PV the number of installations has experienced a decrease in the last years. Despite of the uncertainty of further PV installations, the Italian market is seen to have a high potential for residential storage systems for self-consumption. Only recently Italy allowed the installation of residential batteries without the omission of feed-in tariffs. A new RES regulation which will redefine feed-in tariffs and net-metering is expected to be issued this year 2016. This will set the path for one of the main drivers for residential batteries [RES LEGAL 2016].

With decreasing system costs for both batteries as well as PV and a further increase of electricity costs, a KPMG study expects the retrofit of PV systems with batteries to have a positive return on investment around 2018 in the UK. The installation of new PV+storage systems in the UK will be profitable between 2022 and 2030 [KPMG 2016].

In Figure 41 the expected increase of installed battery capacities for self-consumption for the considered countries is shown. The growth scenario for the other European countries is expected to follow the pace of the UK and Italy. Figure 41 shows that the capacity development until 2020 will be led by the German market. Due to cost decrease of battery systems and due to the trends in reducing or phasing out feed-in tariffs and/or net-metering the growth also in other European markets will accelerate after 2020 leading to an expected installed capacity of almost 4.5 GW in 2025 in Europe.

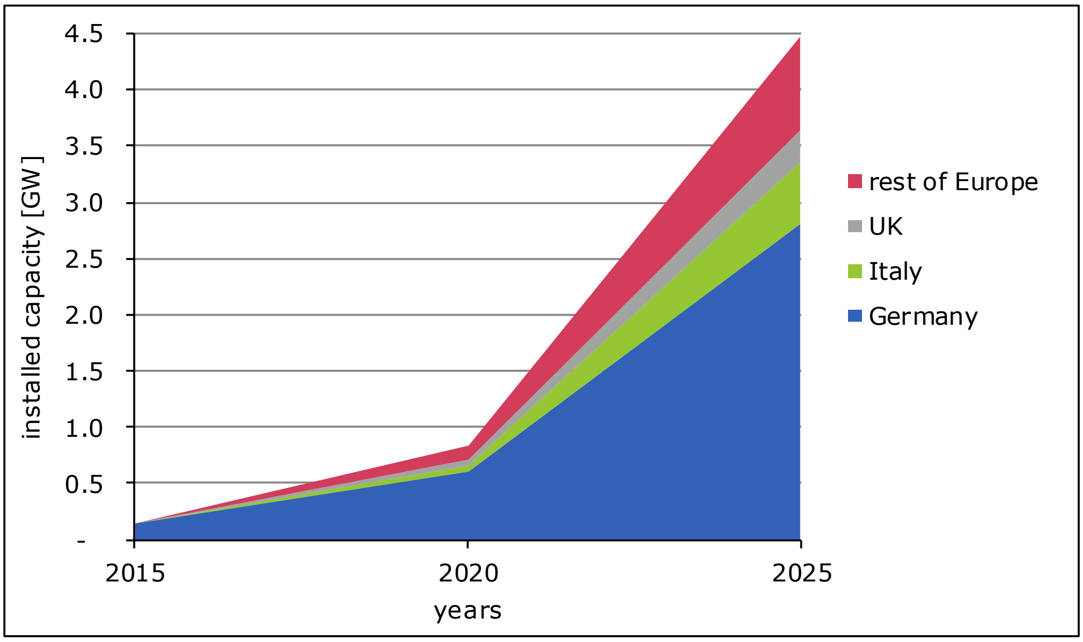


Figure 41: Expected increase of installed battery capacities for self-consumption until 2025 in Europe

Uncertainties remain regarding our assumptions. If countries increase the power components of the electricity prices and basic fees and on the other hand reduce their kWh-prices, battery storage for self-consumption would be less economically attractive. Also uncertainties about the future development of residential PV installations in all European countries exist [Fraunhofer 2015b].

Energy cost management

A large portion of behind the meter energy storage currently relies on three main drivers:

1. Self-consumption of own production;
2. The need to reduce customer peak demand charges that usually occur during periods of high demand;
3. Energy arbitrage which consists of storing energy during off peak periods and using it during periods of high demand.

The first driver is already covered by the previous section on "self-consumption". The projected business model for and deployment of energy cost management in our estimation thus relies on the other two drivers, i.e. differential between peak and off peak electricity rates as well as the amount of demand charges customers are subject to. Both the energy rates as well as the transmission and distribution fee can have prices which vary during the day and/or have a capacity term. The situation varies by country and within a country by retailer, TSO and DSO and by type of contract.

The penetration of distributed energy resources, is currently still the most important driver for small consumers. As this is already covered by the self-consumption service for residential consumers, we will only focus on larger consumers for the energy cost management case as these are also the ones having access to more dynamic tariffs (e.g. an energy contract based on wholesale electricity prices) and are very often subjected to demand charges.

For these consumers we will start from the current values given by the DOE energy storage database (33.84 MW). [DoE 2016] The average annual growth rate of this application's market accounts for 100% over the last five years according to the same database. After this market entry phase, a market ramp up in the coming years can be expected until market diffusion begins between 2020 and 2030 [Fraunhofer 2015a]. We therefore assume a lower and linear growth of 17 MW per year until 2025 representing a 50% growth rate in 2017 and a compound annual growth rate of 21% until 2025. This leads to an installed BESS capacity of 102 MW in 2020 and 187 MW in 2025 for energy cost management.

Back-up power

Battery systems at UPS systems provide the bulk of the installed battery capacity in Europe and the market has been established for decades. The constant growth in the past years has been driven in particular by the telecommunications sector [Agora 2014]. The European market comprises the volume of around two billion euros per year [Frost & Sullivan 2011]. The total output of these systems is difficult to estimate because there is a wide variety of designs (power, capacity, etc.). However, if assuming 2,000 €/kWh[30] for an integrated battery system[31] and an average power/energy ratio of 1 kW/1kWh this would lead to a market size of 1,000 MW/year. With a conservative life expectance of lead acid batteries of 5 years the current installed base comprises 5,000 MW at minimum. Taking the conservative assumption of 1% growth per year due to a possible saturation of the telecommunication sector there will be approximately 5,260 MW installed in 2020 and 5,530 MW in 2025.

6.2.2 Ancillary services

Voltage Support and black start capability

Voltage support and black start capability have been identified as two potential services which can be provided by means of BESS and for which the demand is expected to increase the coming years. Currently however, there are no formal market structures in Europe to offer these services and no uniform rules and regulation, so it is very difficult to estimate the potential role of battery systems in providing these services. Moreover, we assume that batteries won't be installed solely for the purpose of offering one of these services exclusively so the installation of these systems should already be covered by the projections of the other services. Therefore we just keep the current level of deployment from the DOE energy storage database also for the future 2020 and 2025 scenarios as a conservative

---

[30] Pessimistic assumption (high costs) for Lead-acid battery systems in 2011.

[31] Conservative assumption of battery system costs lead-acid in 2011 as stated in "Costs and benefits for deployment scenarios of battery systems (D7)"

estimate (thus assuming that additional growth of these services will be provided for by systems with a 'main other service').

Frequency control

An increasing number of alternatives to the current provision of frequency control in the power supply system by conventional power plants will be required and storage including batteries is seen as one of these alternatives. A battery can quickly and accurately compensate for short-term output deviations from variable renewable energy generators in order to maintain system frequency [IRENA 2015a]. Batteries are therefore specifically suited for the shorter term frequency response services with a limited energy capacity proportion, i.e. Frequency Containment Reserves (FCR) and Automatic Frequency Restoration Reserve (aFRR) [Elia 2016]. Moreover the remuneration for these kind of services is mostly higher (in comparison to manual Frequency Restoration Reserve, mFRR) which makes these types of services more interesting to justify the required investment in batteries [Elia 2016]. We therefore assume that batteries will mainly be used for these services. As mFRR and Replacement Reserves (RR) require energy to be provided over a longer time frame other flexibility options competing with battery storage are better suited. We therefore set our projections for the expected deployment of mFRR and RR to 0 MW.

In addition, some new services could be needed for which batteries might be very suitable. National Grid will for example procure a new faster-acting service - Enhanced Frequency Response (EFR) - aimed predominantly at storage assets including BESS to provide frequency response in 1 second or even less for the UK energy system [National Grid 2015d, National Grid 2016]. We consider this new service in our analysis as this is already being contracted by a European TSO and as projections are available for the UK market.

We therefore include estimations for three types of frequency control:

- **Frequency Containment Reserves (FCR)**
  The introduction of more renewable energy systems with generally smaller system sizes will probably not reduce the design case of 3,000 MW of frequency containment reserves by 2030 which applies to the entire synchronous integrated grid of ENTSO-E [Dena 2014]. In our analysis we will thus use this maximal market potential for both 2020 and 2025;
- **Automatic Frequency Restoration Reserve (aFRR)**
  There are major differences in the aFRR requirements and the use of aFRR by the TSOs throughout Europe. Upward and downward aFRR capacity throughout Europe in 2015 are given in [Entso-E 2016]; In February and June 2015, TSOs applied 7,500-8,100 MW of upward aFRR reserves in Continental Europe and 300 MW in the Nordics and 6,700-7,600 MW of downward aFRR reserves in Continental Europe and 300 MW in the Nordics; Based on these figures, we assume an upper bound of 8,400 MW for downward/upward aFRR within Europe in 2016 for our analysis.
  Projections on future needs of aFRR throughout Europe are not readily available. Some studies however report on national projections; Elia, the Belgian TSO, foresees an increase of 25-36% of aFRR in the period 2017-2027 in a recent study [Elia 2016], whereas German Energy Agency dena foresees an increase in demand for Secondary Frequency Control[32] of

---

[32] Secondary Frequency Control (SFC) overlaps with aFRR.

approximately 10% for downward and 40% for upward balancing energy until 2030. As European estimates are lacking, we assume a moderate and symmetric growth rate of 10% by 2020 and 20% by 2025 for aFRR throughout Europe;

- **Enhanced Frequency Response (EFR)**
  National grid starts from a base assumption of 225 MW of Enhanced Frequency Response in the UK by 2020. Looking longer-term, an increase in requirements is expected during summer periods. Under different future energy scenarios Enhanced Frequency Response capacities are needed between 225 MW and about 1,000 MW by 2025 in the UK [National Grid 2015b].

This leads to the following projections for the three frequency control services identified as most appropriate for battery storage.

Table 8: Projections on the future need of EFR (UK), FCR and aFRR within Europe

Service	Current	2020	2025
EFR	0 MW	225 MW	225-1,000 MW
FCR	3,000 MW	3,000 MW	3,000 MW
aFRR	8,400 MW	9,240 MW	10,080 MW

It is very difficult to predict the expected proportion of these services which will be met by means of Battery Energy Storage instead of other flexibility means such as conventional power plants, demand response, other storage solutions, etc. As the current deployment of batteries to provide ancillary services is still rather limited, we propose to take into account an expected range of deployment of battery systems for the different services; Assuming that 10-50% of projected EFR and FCR capacity and 10-20% of aFRR capacity can be provided by battery storage, 1.2 – 3.5 GW of battery-based storage capacity could be deployed in 2020 to provide frequency control, whereas a capacity of 1.3 – 4.0 GW could be deployed in 2025. A distinction based on the type of service can be found in Table 9.

Island operation capability

European islands in the Mediterranean sea (e.g. Sardinia and Sicilia), the Atlantic Ocean (e.g. Orkney and Pellworm) as well as further remote islands such as the Azores (Portuguese islands in the Atlantic Ocean) and Guadeloupe (insular region in Caribbean), have a high and already well noticed potential for battery storage. Battery systems can increase the share of renewable energies and therefore reduce the dependency on diesel and coal that needs to be shipped in and is highly price volatile. Many of the European islands have the advantage to be placed in tropical and sub-tropical regions that show low seasonability within their solar irradiation which enables a high share of PV with short term storage systems, such as batteries [Blechinger 2014]. Islands in Northern Europe are better suited for wind energy. Storage systems that would enable a higher share of wind energy on islands would need a higher capacity to store energy over a longer time. Therefore islands in the Mediterranean sea or Caribbean will be most likely to install batteries while for northern countries technologies like flow batteries could be suitable.

In recent years many battery projects for islands have been tendered and procured. To name a 2 MW/3 MWh Sodium-Nickel-Chloride at Tilos a Greek island under the Horizon 2020 programme [Tilos 2014], the 2.6 MW lithium-ion battery on Graciosa, a Portuguese island [Younicos 2016] or the 0.2 kW/1.6 MWh Redox-Flow Battery on Pellwork a German island as three examples.
All of the so far commissioned batteries adding up to 20 MW (built and procured) plus another 60 MW that is planned or tendered and therefore expected to be built within the next five years are running under pilot status. However with increasing knowledge gained over time and reducing battery and PV costs the installed capacity will increase drastically in the future. One indicator is the development on French islands that tendered up to 50 MWh of battery storage for its islands and offshore territories in the Atlantic, Pacific, and Indian Oceans, and for Corsica in the Mediterranean Sea [Gifford 2015].
Factors still hindering the acceleration of battery deployment are the high initial investments and low information levels of decision makers [IRENA 2015b].

A study by the Rainer Lemoine institute assessed the global potential for batteries on small islands (1,000 – 100,000 inhabitants) to be more than 5.3 GWh [Blechinger 2014]. Assuming that one firth of this potential lies within the European islands and adding the already planned capacity and the potential of greater islands (such as Corsica, > 300,000 inhabitants) this results in a potential of 1,200 MW[33] for batteries on European islands. How much of this will be installed until 2025 is uncertain, we assume a conservative linear growth that would lead to an installed capacity of 100 MW.

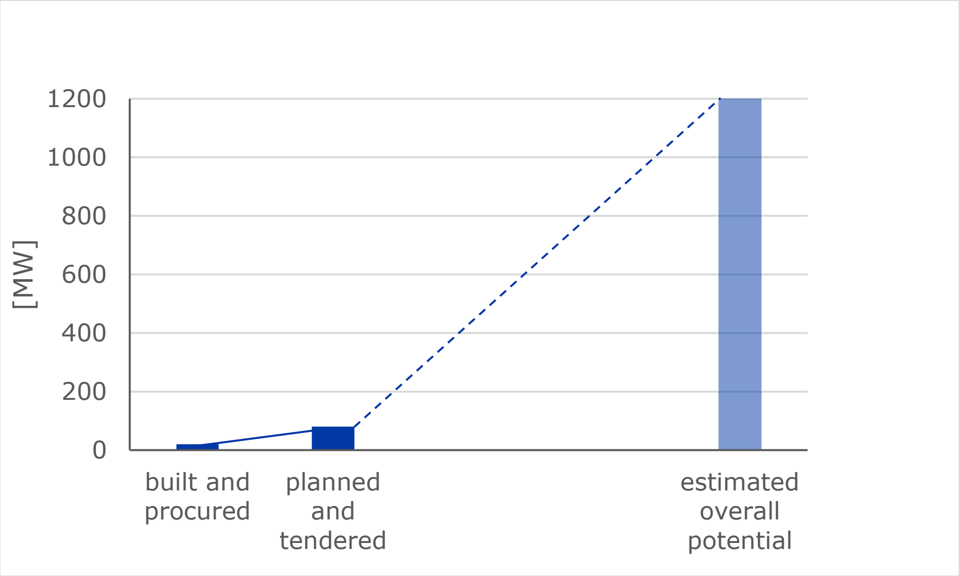


Figure 42: „Built and procured", „planned and tendered" and „estimated overall potential" for batteries on European islands

---

[33] A C-rate of 1 MW/MWh has been assumed as this ratio has been the most common within the already built and tendered projects (Own calculation based on the projections from [Blechinger 2014]).

6.2.3 T&D system applications

Grid congestion relief and grid upgrade deferral

Battery based energy storage can be applied to avoid grid congestion during peak periods and/or to defer grid upgrades. There are a number of drivers that are expected to lead to increasing peak demand for capacity in distribution and transmission grids:

- Increasing renewable energy penetrations on distribution level, in particular solar PV that can have a major impact on peak power flows in towns and cities. Secondly, there can be significant concentration of this RE in areas that are particularly favourably situated;
- Likely increase of renewable energy distribution from large scale developments in areas with high generation sources (for example solar PV in the south of Europe), where at times significant volumes of power need to be transported on transmission level to Northern and Central Europe load centres;
- Growth in penetration and capacity of electrical vehicles including their charging infrastructure;
- Increasing electrification of heating, for example with heat pumps that can lead to new peak demand periods during times with cold weather.

Moreover, the cost advantage of flexibility solutions in comparison with grid upgrades will decide if the role of batteries within this application will grow. Battery based energy storage may be a cost-effective alternative to grid upgrade or other solutions only at low-voltage level. Storage in medium- and high-voltage grids will only play a minor, negligible role. A recent study of distribution grids in Germany determines that only high RES penetration levels enable a business case for BESS. The study proposes an installed BESS capacity for grid upgrade deferral close to zero in 2023 and 700 MW in 2033 as higher RES penetration levels will be reached [Agora 2014].

German distribution grids roughly account for 18% of the total length of distribution lines in all of Europe [Eurelectric 2013]. Keeping in mind the higher RES penetration rates already today and targets set by the German government, we assume 2 GW of installed BESS capacity for grid congestion relief and/or grid upgrade deferral by 2033 in Europe. 20% of this capacity (400 MW) may already be in place by 2025. Starting point for our projection is the DOE database stating as current 15 MW installed capacity for grid congestion relief and 9 MW for grid upgrade deferral.

Substation on-site power

BESS provide power at substations in case of grid failure. Primary growth drivers for this application are load growth on specific substations, electric vehicle deployment and penetration of distributed energy resources. These factors may lead to grid upgrade, hence more substations that would to be equipped with BESS.

The limiting capacity factor in a substation is the transformer. As battery based storage at transmission level is negligible, we look at the total number of medium- and low-voltage transformers in Europe, which is about 4 million. A ratio of one transformer per 2.45 km of distribution circuit length can be found [Eurelectric 2013]. A study of the expansion of German distribution networks assumes a network expansion requirement of about 200,000 km to be constructed by 2032 [BMWi 2014].

Again, extrapolating this figure for all European distribution networks while respecting Germany's share and pioneering role, we assume 200,000 km to be added to Europe's distribution networks by 2020 and 350,000 km by 2025. Accordingly, about 80,000 transformers will be installed by 2020 and about 140,000 transformers by 2025. Assuming a BESS capacity of 3 kW per substation this leads to 2.4 MW of installed BESS capacity for substation on-site power by 2020 and 4.2 MW by 2025. Starting point for our projection is again the DOE database stating 0.5 MW currently installed capacity for this application.

6.2.4 RES applications

Energy revenue optimisation and VRES integration

According to the DOE database there is an installed BESS capacity of 12.3 MW for this application [DoE 2016]. In Germany 1.16% of the total volume of electricity generated in 2014 by RES was not fed into the grid as a result of feed-in management measures. This number rose almost threefold from the previous year. 77.3% of the curtailment took place at wind power plants and 15.5% at PV systems [BNetzA 2016].

Today the installed wind power capacity in Europe is 139 GW and there is 86 GW of installed solar power. Up until 2020 these capacities are likely to grow by 16.5% and 17.5% respectively. From 2020 to 2025 the further growth is expected to be 41.4% and 44.5% [ENTSO-E 2015c].

The expected curtailment gives a good indication on the future VRES integration need that cannot be solved by other means of flexibility. A recent analysis by Fraunhofer of the EU power system provides quantitative information on the expected growth of curtailment within the scenarios ranging from "high efficiency of demand" to "moderate efficiency of demand". Until 2030 RES-E curtailment is below 1%. Thereafter, curtailment increases to 4.9% in 2050 [Fraunhofer 2014]. Another study carried out by DNV GL assumes a significant increase in curtailment of RES-E after the year 2025 and a maximum curtailment of 1.6% in 2030 [DNV GL 2014].

Taking this all into consideration, we assume that the curtailment ratio will not increase significantly but installed capacities of wind and solar power will. Applying their growth rate to the installed BESS capacity we conclude that there may be 14.4 MW in place by 2020 and 20.4 MW in 2050.

6.2.5 Summary of battery storage application projections

Table 9 sums up our projections for battery based energy storage based on the current status and main growth drivers for 2020 and 2025. Taking into account the assumptions from the previous section, the installed BESS capacity today amounts to 5,320 MW. We expect a total capacity between 7,600 MW and 9,800 MW could be reached by 2020 and between 11,500 MW and 14,500 MW in 2025. The main applications are and will be self-consumption and backup power while we are also seeing considerable potential for energy cost management, frequency containment reserve, automatic frequency restoration reserves and grid congestion relief.

It should be noted that our projections are relying on a variety of studies and input from stakeholders. Our assumptions are subject to uncertainties in technology and market developments as well as regulatory frameworks. Refinement of these projections continues as we are still collecting information.

Table 9: : Summary of battery storage applications projections

Application	Main growth driver	Installed BESS capacity in 2016:	Projection BESS capacity in 2020	Projection BESS capacity in 2025
Self-consumption	Residential PV systems installed, grid parity of PV systems	144 MW	876 MW	4,080 MW
Energy cost management	Differential between peak and off-peak pricing	34 MW	102 MW	187 MW
Backup power	Expansion of telecommunication and other relevant industries System Average Interruption Duration (SAIDI)	5,000 MW	5,260 MW	5,530 MW
Voltage Support	RES penetration, system need and development of conventional providers	17 MW	Min 17 MW[34]	Min 17 MW
Enhanced Frequency Response (EFR)	System inertia	0 MW	23-113 MW	23-500 MW
Frequency Containment Reserves (FCR)	RES penetration, system need and development of conventional providers	88 MW	300-1,500MW	300-1,500 MW
Automatic Frequency Restoration Reserve (aFRR)	RES penetration, system need and development of conventional providers		924-1,848 MW	1,008-2,016 MW
Manual Frequency Restoration Reserve (mFRR)	RES penetration, system need and development of conventional providers		0 MW	0 MW
Replacement Reserves (RR)	RES penetration, system need and development of conventional providers		0 MW	0 MW
Black start capability	Regulatory requirements to provide black start from the distribution grid / with batteries	2 MW	Min 2 MW[35]	Min 2 MW
Island Operation Capability		10 MW	60 MW	100 MW
Grid congestion relief **Grid upgrade deferral**	RES penetration (and costs of alternative solutions)	15 MW 9 MW	30 MW	400 MW
Substation on-site power	Grid expansion with increasing numbers of substations	0.5 MW	2.4 MW	4.2 MW

---

[34] Assuming that the installed battery capacity will remain in the grid

[35] Assuming that the installed battery capacity will remain in the grid

Application	Main growth driver	Installed BESS capacity in 2016:	Projection BESS capacity in 2020	Projection BESS capacity in 2025
Energy revenues optimisation **VRES integration**	Renewable energy curtailment	12 MW	14 MW	20 MW
SUM		5,320 MW	7,600 – 9,800 MW	11,500 – 14,500 MW

7 Socio-economic impact of batteries

In this chapter we will analyse the socio-economic impact of battery storage within the European energy system, starting from our projections on battery deployment for 2020 and 2025 where possible. Economic, environmental and social indicators are covered. In addition, we will look into the current and future battery industry in Europe.

7.1 Socio-economic indicators

7.1.1 Economic indicators

The introduction of large amounts of battery based energy storage in Europe will have significant impacts on the growth of the industry locally, but also globally throughout the energy storage supply chain. As set forth in the European Commission's 10 targets "Towards an Integrated SET Plan" [EC 2015a] and in the BATSTORM Implementation Plan [BATSTORM D8], the EU is poised to play a key role in advancing the technology and reducing its costs, thus contributing to making more and more energy storage applications cost-effective. This section outlines the annual battery sales projections and highlights how they translate into economic growth factors such as employment. It's important to note that there is very limited (especially quantitative) information on this topic and the industry is in the early stages of development. Therefore, there are many challenges to assessing the economic impact of energy storage deployment scenarios.

The economic effects of growing battery demand in the future can be summarized as follows:

- European battery sales will increase from USD 60 million in 2014 to USD 5 billion until 2023 for utility-scale applications. [INSIGHT_E 2014, IRENA 2015a];
- The battery market for behind-the-meter applications currently exceeds the market volume of batteries for utility-scale applications and adds up to 2.1 billion € in 2015. The market is expected to grow and will reach a market volume of approximately 5 billion € in 2025. [AGORA 2014, RWTH 2016];
- Growing demand of battery cells will create the need of increasing production capacity in Europe; thus creating 4,000 jobs directly or indirectly linked to cell production. [NPE 2016];
- Newly established cell production capacities and overall growing demand of battery systems will foster and strengthen all industries along the battery storage value chain leading to up to 50,000 additional jobs. [REA 2016, KEMA 2010].

European battery market – annual sales

The battery market for the energy system has seen significant growth in recent years. For utility-scale applications (excluding battery storage installed behind-the-meter), global revenue was around USD 220 million in 2014 of which USD 56 million can be attributed to Europe as can be seen in 43 according to [IRENA 2015a] and this market is expected to grow in the coming years. The annual revenue is expected to increase from USD 220 million in 2014 to USD 18 billion in 2023, of which more than USD 5 billion would be sold within Europe. [INSIGHT_E 2014] Additionally to the utility scale applications, the European market for back-up batteries has a market volume of two billion € and the market volume is constantly growing. [AGORA 2014] Furthermore the market volume for residential and commercial storage systems, that are placed behind-the-meter cannot be neglected. The price for a rather cheap system including full equipment and installation costs, is around 1,500 €/kWh. [RWTH 2016] With up to 100 MW batteries installed behind-the-meter in Europe in 2015, this adds up to a total battery market of 150 Million €. Therefore the market volume for batteries in use behind-the-meter is currently much larger than for utility scale applications and adds up to 2.1 billion in 2015. With the expected evolution of increasing demand for behind-the-meter applications in combination with cost reductions for battery systems, the market volume is expected to increase to around 5 billion € before 2025.

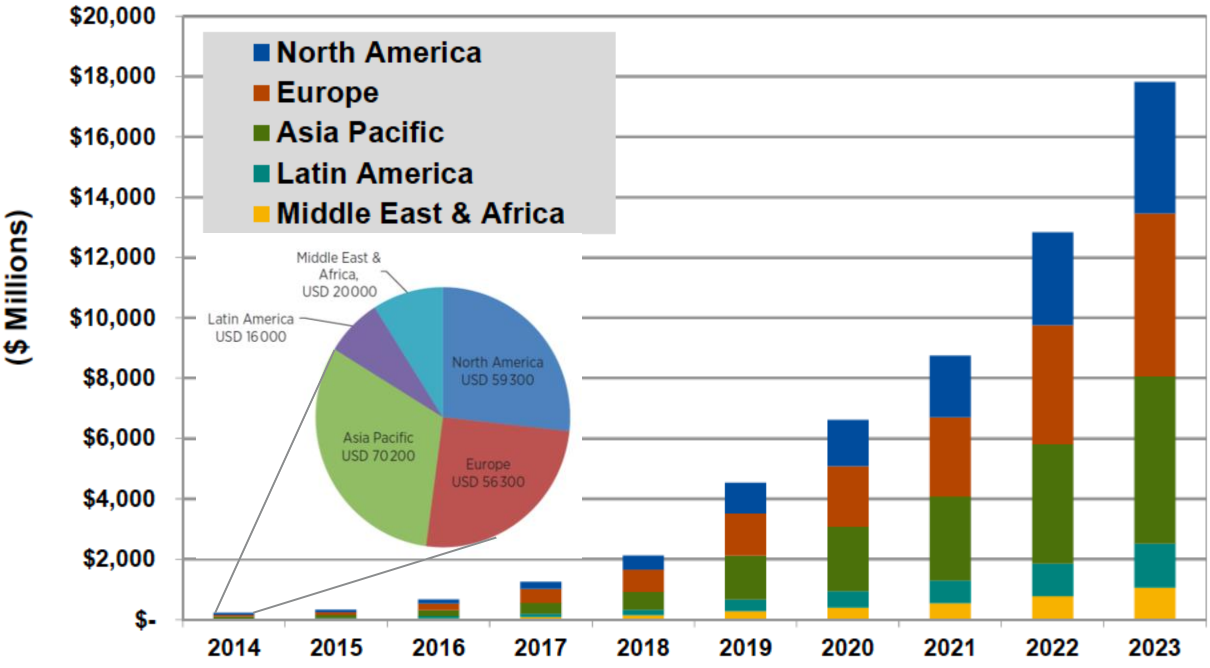


Figure 43: Battery storage cell sales for utility-scale applications in 2014 and projections until 2023 in different regions[36] [IRENA 2015a, INSIGHT_E 2014]

Employment

According to EUROBAT, the EU automotive and industrial battery sector currently directly employs around 30,000 workers. This figure reflects only the manufacturing and research aspects of the industry and does not account for the thousands of dependent jobs across the supply chain, including those located in the recycling industry. [EUROBAT 2016a]

Europe's battery industry is especially strong regarding research, materials and components (Umicore being the worldwide market leader in Cathode materials), system design and system integration. In these fields most employees can be found. Furthermore, engineering firms that design machinery and equipment for companies along the value chain have a high share of the overall jobs related to battery

---

[36] Battery systems at UPS systems are not included in this figure.

storage. Figure 44 shows different sites of companies along the battery storage value chain for the German case. [VDMA 2015]

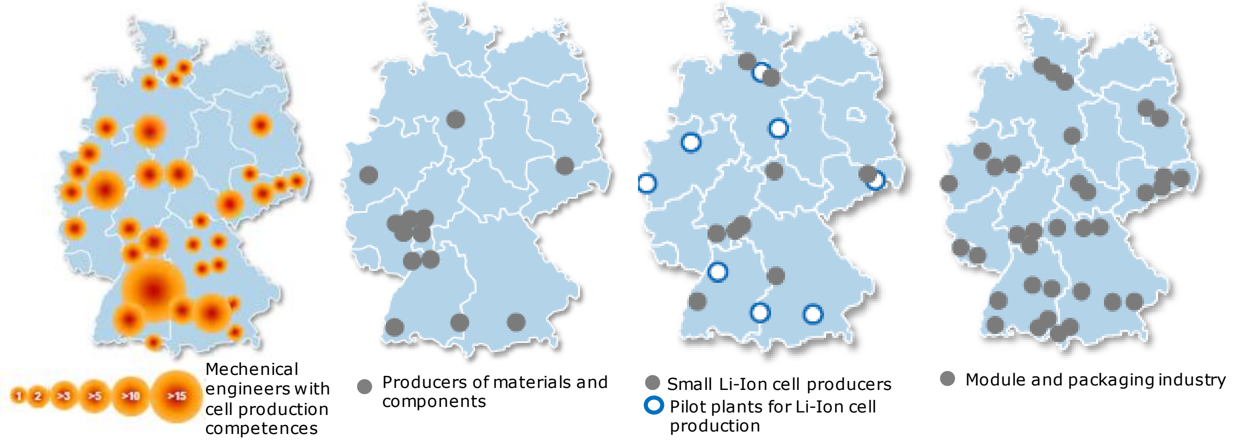


Figure 44: Different battery industries along the value chain in Germany (no claim of completeness) [VDMA 2015]

According to our projections on installed battery capacity, more than 10,000 MW of battery systems will be installed additionally up until 2025. While the United States and Asia are currently upscaling production capacities, in Europe the gap between battery demand and battery supply is increasing. A study shows that until 2020 the production capacity has to thirteen fold in order to match the demand of stationary battery systems and batteries for electric vehicles of the future. [VDMA 2015] If cell production will take place outside Europe, some industry players are scared the competitive position of other industries within the value chain will also decrease. Furthermore, this could lead to supply bottlenecks which are already the case for some European car manufacturers ordering cells from Asia. [Interviews with stakeholders, IT-Times 2016]

Establishing a cell production industry would have major effects on employment in Europe. A study by the German national association for electro mobility [NPE 2016] estimates that 1,050 to 1,300 new jobs would be created directly linked to cell production in a plant that produces 13 GWh/year[37] of batteries. Of those 750 – 900 would be direct employees working in shifts. Cell production can be highly automated and therefore only 190 – 225 employees would be needed per shift according to the study. Furthermore 150 - 200 employees can be expected in administration, procurement and sales and again 150 – 200 in business related research and development. Additionally to the directly employed, more than 3,000 jobs could be created within the region of the cell producing plant. Benefiting industries could be suppliers, subcontractors, logistics as well as mechanical engineering, construction and automatization companies. [NPE 2016] These numbers only regard additional jobs created in the near environment of a cell production plant. However, the industry states that all other industries along the value chain would benefit from an established cell production industry. The successful position of Europe within the international cell production market will therefore foster and strengthen also the other parts of the value chain. [VDMA 2015]

---

[37] 13 GWh/year exceeds the projected number of the capacity growth projections in this report. The study additionally includes batteries for e-mobility and industries as main drivers.

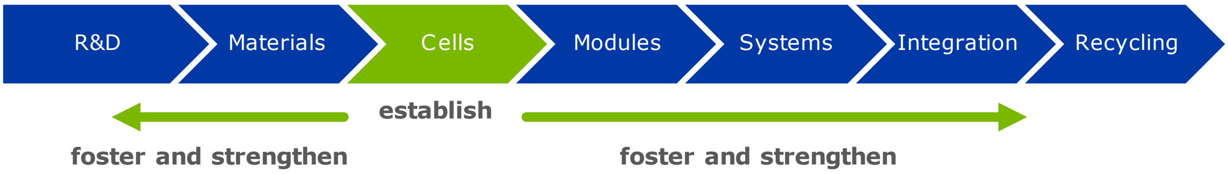


Figure 45: Impact of cell production along the value chain

These numbers illustrate the effects of a new Li-Ion cell production plant. In addition, the overall increase of battery installations in all different business cases will increase the demand of materials, modules and systems. This will generate additional job opportunities at the already existing players. Furthermore, the growing demand of other battery technologies than Li-Ion such as Redox-Flow and Lead acid has a high potential of creating new job opportunities.
Studies calculated that installing 2,000 MW of new storage would provide new employment opportunities for up to 10,000 people. If 10,000 MW will be installed as foreseen in section 6.2, this could add up to 50,000 jobs[38]. [REA 2016, KEMA 2010]

A specific case study which has modelled the impact of storage on employment in for Massachusetts is presented in the box below [DOER MASSCEC 2016].

---

[38] This is based on an assumption that £200,000 creates one direct or indirect employee. [KEMA 2010]

Massachusetts case study – modelling the impact on employment

A study of the Massachusetts Energy Storage Initiative "State of Charge" assessed the impact on employment of incremental investment in energy storage in Massachusetts by applying an economic impact model known as IMPLAN[1]. The model measures demand-side stimulus actions, such as increased sales to local industries or firms and derives the impact on employment. In the results illustrated hereafter, the economic impact of 1,766 MW of energy storage deployment was the creation of 5,900 job-years[2] (Figure 47) – which is equal to approximately 1,200 individual jobs and over $550 million in labour income (Figure 46) over the five years studied.

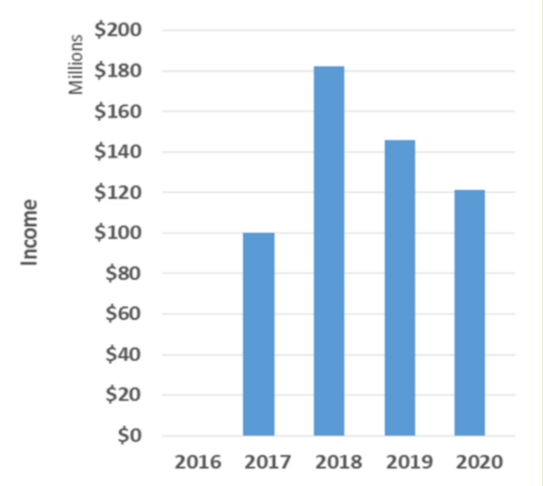


Figure 46: Massachusetts Labour Income Impact

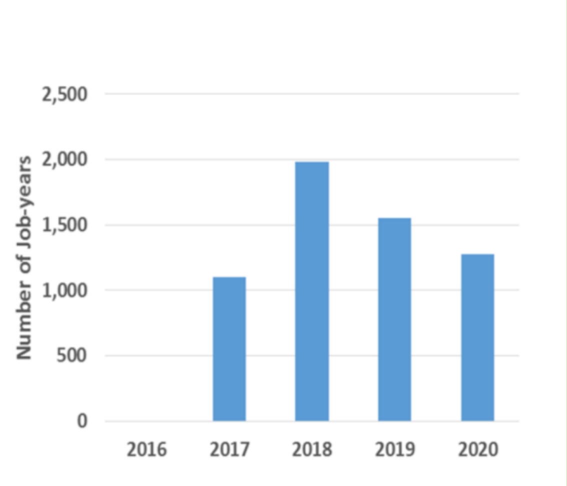


Figure 47: Massachusetts Employment Impacts

The main industries that contribute to the deployment are "Storage Battery Manufacturing", "All Other Miscellaneous Electrical Equipment and Load Manufacturing", and "Electric Power Transmission and Distribution". The declining costs of energy storage result in lower $/MW economic activity as the technology matures.

---

[1] https://implan.com/

[2] Job-Years is defined as one job for an entire year.

7.1.2 Environmental indicators

Energy storage, including batteries, can deliver different advantages to the energy system and can thus be seen as an essential technology for grid optimization. Energy storage, including batteries, can help to integrate more renewable energy sources. First, it can reduce the need for curtailment by time-shifting renewables. Second, when sited in areas with congestion or increasing amount of distributed renewable energy, energy storage can help reduce reverse power flows. In addition, optimizing the grid by means of storage, provides for greater savings of primary energy resources such as coal, petroleum, natural gas, etc. Moreover, energy storage can effectively be used to mitigate the variability of renewable electricity production and thus alleviate the ramping requirements for baseload generation. This could improve the overall efficiency of the system and thus also contribute to reducing primary energy fuel consumption and accompanying greenhouse gas emissions. Evaluating the costs and benefits of individual energy storage projects can be relatively straightforward, however determining the impact of large amounts of storage on the grid requires an in-depth and costly analysis.

When determining the environmental impact of deploying battery storage in the energy system, both the impact during construction as well as the impact during operation has to be taking into account, including the recycling phase. Typically a Life Cycle Assessment (LCA) is used to determine this impact. Determining the impact during the lifetime of the battery requires an analysis that simulates grid operations with and without energy storage. The results of this analysis are very much dependant on the service(s) which are provided with the battery system and on the characteristics of the energy system. In this case system scenario modelling and resource dispatch optimization for the considered system are necessary. In any case the environmental impact of battery storage over its entire life cycle should be compared with the impact of competing technologies to offer similar services, so the deployment of battery storage can potentially even decrease the environmental impact on the overall energy system. LCA and energy system modelling are not part of the scope of this study however we reviewed the main studies in this space and highlight the main learning in this section. These studies typically focus on one battery technology offering one service or a combination of services in a specific region/country or setting. We mainly focus on **primary energy use/savings**, **greenhouse gas emissions (mostly CO_2)**, **material use** and **end of life options**, i.e. the reuse or recycling of batteries..

In [Sullivan et al 2012] an overview is given of different battery life-cycle assessments for the main battery technologies: lead-acid (PbA), nickel–cadmium (NiCd), nickel-metal hydride (NiMH), sodium-sulfur (Na/S), and lithium-ion (Li-ion) batteries. Only the construction phases are considered, i.e. battery material production and component fabrication and assembly into purchase ready batteries or the so-called cradle-to-gate (ctg) approach. Battery integration, operation and end-of life options are not considered in this study. The study mainly looks at cradle-to-gate energy use and emissions. Average cradle-to-gate carbon dioxide emissions per kg of battery are presented in Figure 48. **CO_2 emissions** are lowest for PbA, higher for NiCd, and highest for the remaining advanced technology batteries. Due to the magnitude of the variation seen in the figure, the average CO_2 values for Li-ion, Na/S, and NiMH are concluded to be statistically equivalent in the study. As can be seen in Figure 49, the magnitude of battery **cradle-to-gate energy** follows the same trends as the CO_2 emissions. It is again clear that PbA has the lowest production energy, followed by NiCd batteries. Also here, the energy values for Na/S, Li-ion, and NiMH batteries are considered to be statistically indistinguishable. The figure also shows that using recycled materials during manufacturing can significantly reduce the energy use. Figure 50 presents the same information but distinguishes between the contribution of manufacturing and material production to the energy use. Energy use during material production is about two thirds for PbA and Na/S and about half for NiMH, Li-ion, and NiCd. Again, these trends must be considered provisional, given the variation of the data. The study further notes that while the cradle-to-gate energy and emission burdens of battery production are significant, the relative implications of those impacts on the life-cycle performance of a battery application can be quite small. In effect overall life-cycle energy and emissions savings can be realized when comparing the environmental impact of batteries with other competing technologies.

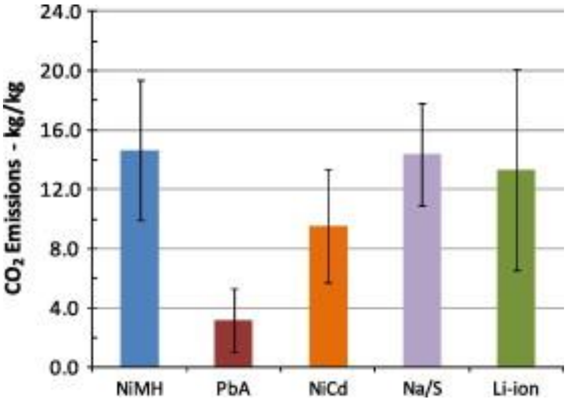


Figure 48: Average Cradle To Gate CO_2 emissions for the production of a kg of indicated batteries [Sullivan et al 2012]

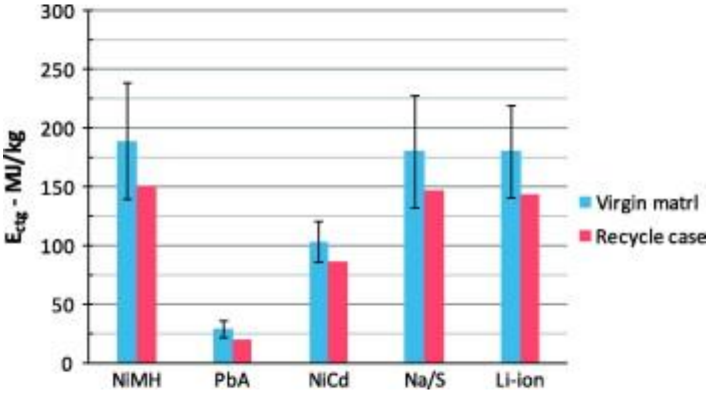


Figure 49: Average Cradle-to-gate energy for various battery technologies using respectively virgin and recycled (virgin to recycled material content of 30/70) materials [Sullivan et al 2012]

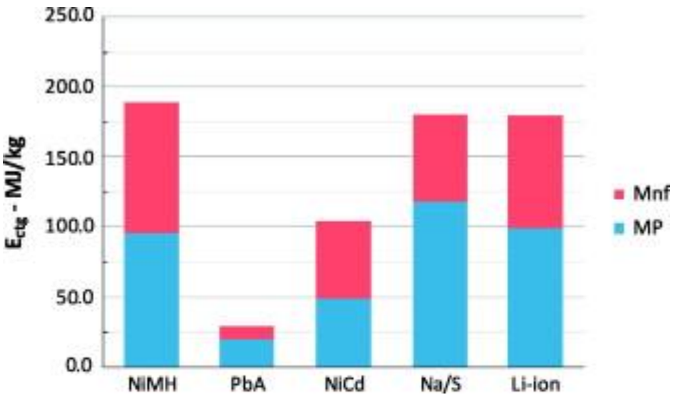
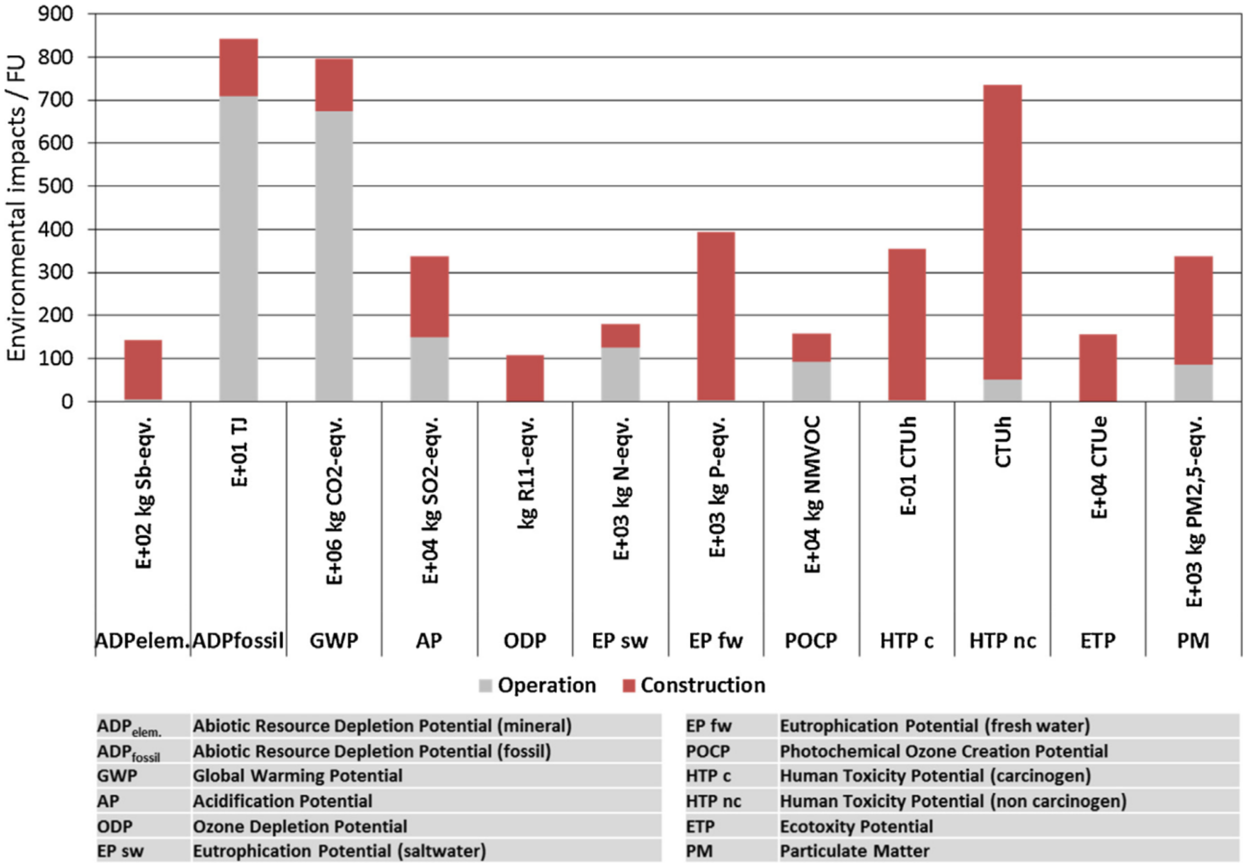


Figure 50: Average Cradle-to-gate energy for various battery technologies during manufacturing (mnf) life-cycle stage and material production (mp) life-cycle stage [Sullivan et al 2012]

One recent study which takes into account both the construction and operation phase and compares the impact of competing technologies is presented in [Stenzel et al 2016]. In this study, the environmental impact of providing Frequency Containment Reserves (FCR) by novel Li-ion batteries are compared to the impact of FCR provision by state-of-the-art coal power plants using a Life Cycle Assessment (LCA) approach and considering the German ancillary services market. The LCA analysis is based on JRC's recommendations as described in the International Reference Life Cycle Data System Handbook [JRC 2011]. Impacts caused by the construction of BESSs and their operation for FCR provision over 20 years for twelve impact indicators are shown in Figure 51. The figure illustrates that the environmental impacts caused by BESSs are dominated by the construction phase in many categories. For **energy use** (indicated here as *"Abiotic Resource Depletion Potential (fossil)"*) and **CO_2 emissions** (indicated here as *"Global warming potential"*) the operational part is however largely dominant as was also stated in [Sullivan et al 2012]. As the environmental impact is highly dependable on the composition of the electricity consumed by BESSs during the operational phase, an electricity mix with higher shares of renewable energy – as will be the case in the future - would even lower the contribution of the operational phase to the environmental impact.



$ADP_{elem.}$	Abiotic Resource Depletion Potential (mineral)	EP fw	Eutrophication Potential (fresh water)
ADP_{fossil}	Abiotic Resource Depletion Potential (fossil)	POCP	Photochemical Ozone Creation Potential
GWP	Global Warming Potential	HTP c	Human Toxicity Potential (carcinogen)
AP	Acidification Potential	HTP nc	Human Toxicity Potential (non carcinogen)
ODP	Ozone Depletion Potential	ETP	Ecotoxity Potential
EP sw	Eutrophication Potential (saltwater)	PM	Particulate Matter

Figure 51: Contribution of life cycle stages to environmental impacts of batteries [Stenzel et al 2016]

The environmental impact indicators of batteries as shown in Figure 51 should however be compared with the indicators from competing technologies to judge the environmental impact, in this case coal power plants. Results in [Stenzel et al 2016] suggest that the use of batteries can result in a significant reduction of environmental impacts caused by FCR provision when compared to FCR provision by means of coal power plants for all indicators but one, i.e. the impact on material use (indicated here us *"Abiotic Resource Depletion Potential (mineral)"*) which is higher for BESS in all scenarios. Here, this impact is especially provoked by utilization of mineral based materials for cells, inverters and electronic equipment. As already mentioned, the results of these kind of studies are very dependent on the service provided by the battery, the generation fleet of the considered energy system and the availability of competing flexibility options as other technologies might also contribute to the service provision so that results cannot be generalized.

Another important factor when considering the environmental impact of batteries is the choice whether to **reuse or recycle** batteries. According to Lux Research [Lux Research 2016] recycling, rather than reuse, is likely to be the more attractive option. Reuse of batteries from electric vehicles will for example deliver questionable returns due to reduced performance, limiting them to services with less frequent and shallower depth of discharge cycles, according to their analysis. With present technology, recycling old batteries for new materials is the more economical option for creating the most value from existing materials. However, with more efficient testing, sorting, and repackaging, **second-life systems** could be made more competitive for certain applications like demand response and backup power. According to EPRI [EPRI 2016] cost-effective **reuse** and **recycling** strategies should be possible for all battery technologies, including lithium ion. Currently 96% of lead-acid batteries are recycled. Replicating the lead-acid battery industry's infrastructure of independent recycling companies for lithium ion batteries might however not be straightforward. Lead-acid batteries are easier for recyclers to process because they are more uniform in chemistry and configuration. The variety of lithium ion batteries presents an issue. Another challenge is the lack of resale value for the battery components, e.g. Lithium is cheaper to mine than to recycle. [EPRI 2016] In general, both the recycle and reuse paths should thus be considered and further investigated.

Different studies made an attempt to gain a deeper understanding of how energy storage can be optimally deployed under different grid conditions and to estimate the consequences on primary energy savings as well as GHG emissions, without considering the environmental impact during construction of the batteries. It's again important to note that the case studies discussed hereafter are highly dependent on local grid conditions. The cases are referenced here to help understand the variables that influence the value proposition of energy storage under comparable grid conditions. The most recent examples are provided by two studies from the U.S., i.e. the Massachusetts Department of Energy Resources "State of Charge" study [DOER MASSCEC 2016] and the work completed by the California Energy Storage Alliance [CESA 2015] with Plexos.

In the case of Massachusetts, the analysis evaluated and quantified the potential benefits of deploying energy storage across the state and determined the optimal amount of storage to be added over the next five years. The model found that 1,766 MW of storage distributed throughout a network made up of 1,497 nodes and 250 substations could reduce GHG emissions by more than 1.06 million metric ton (MMT) CO_2 over a 10 year time span and is equivalent to taking over 223,000 cars off the road over the same time span. The simulation results over a 5 year period are illustrated hereafter for both CO_2 and NO_x. It's important to note that natural gas and coal account for 54% of the generation mix in Massachusetts, providing a significant opportunity for emission reductions through energy storage. In addition to the positive impacts on CO_2 and NOx emissions the storage program has positive impacts on wholesale electricity costs since it lowers the compliance costs related to GHG emissions.

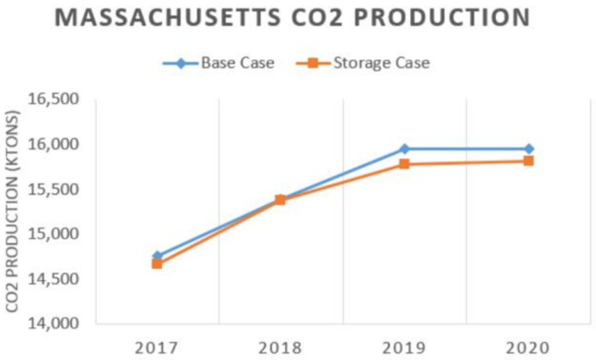


Figure 52: Massachusetts CO_2 production comparison between cases in short ktons per year

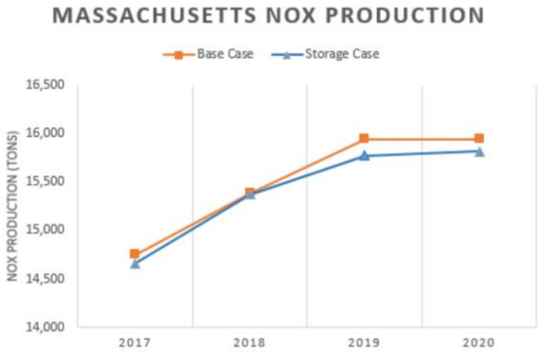
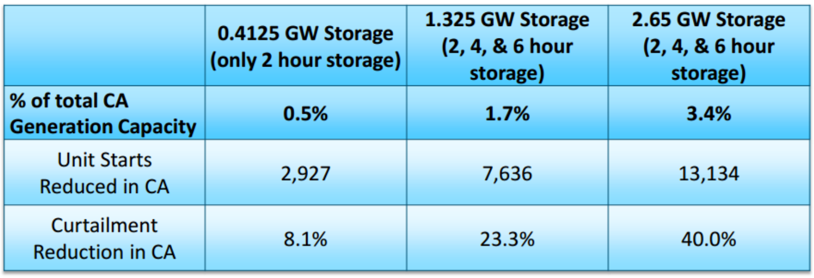


Figure 53: Massachusetts NOx production comparison between cases in short ktons per year

To understand the impact of energy storage in California, the California Energy Storage Alliance mandated a study performed by Plexos that simulated the grid in 2024, with 40% renewable energy. The goal of the study was to quantify system-level **grid emissions**, **unit starts**, and **avoided curtailment** resulting from energy storage to inform decision making at the California Public Utilities Commission. The model found that with 413 MW of 2-hour storage, the net emission savings was 203,677 tons of CO_2. The savings are the result of an 8 percent reduction in the amount of curtailment as well as almost 3000 avoided generation unit starts.



	0.4125 GW Storage (only 2 hour storage)	1.325 GW Storage (2, 4, & 6 hour storage)	2.65 GW Storage (2, 4, & 6 hour storage)
% of total CA Generation Capacity	**0.5%**	**1.7%**	**3.4%**
Unit Starts Reduced in CA	2,927	7,636	13,134
Curtailment Reduction in CA	8.1%	23.3%	40.0%

Figure 54: Results of Production Cost Modelling with Storage

Both studies show significant savings in the amount of GHG emissions as a result of large-scale storage deployments. The primary driver for savings in these studies is the ability to avoid thermal generator unit starts and in certain cases entirely eliminate their use. One limitation of these studies is that they don’t take into account the GHG emissions related to manufacturing and building the energy storage systems.

In the study completed by the California Energy Storage Alliance, the introduction of amounts of energy storage equivalent to 0.5% to 3.4% of generation capacity result in 9% to 30% reduction in unit starts. Under the storage scenarios, 3-4 emergency peaker natural gas plants were removed from dispatch and were no longer operational in California. Another finding of the California study is that an important factor in reducing GHG emissions is the necessity for storage to charge from low emission resources. When the storage system is purely driven by economic factors it tends to multiply “energy arbitrage” dispatch which sometimes means importing cheap energy from fossil fuel resources and discharging them during periods of high demand. In that case, energy storage can actually increase the amount of GHG emissions.

7.1.3 Social dimension

The social dimension of energy storage has two components. The first is the ability of the technology to increase the wellbeing of populations by displacing grid related air emissions with high environmental and health impacts. The second relates to the cost of living and the ability to use energy storage to lower electric bills or gain access to better energy services. We will limit our analysis to the latter dimension, i.e. the ability of storage to reduce energy costs. Energy storage can reduce the cost of energy directly at the customer meter by allowing more solar self-consumption or lower electric bills by capping demand charges or doing energy arbitrage. However, the true savings appear at the system level with the following factors:

- **Reduced Peak Demand**: energy storage can defer capital costs in peaking capacity and reduce the costs of procuring capacity;
- **Reduced Costs of Ancillary Services**: Overall reduction of the costs of ancillary services by using energy storage;
- **Energy Cost Reduction**: energy storage is used to redistribute cheap energy during peak demand periods, limiting the need to costly generators;
- **T&D Cost Reduction**: energy storage is used to defer investments in costly infrastructure upgrades.

The integration of variable renewable generation, accompanied with increasing electrification driven by transport and heating, may lead to degradation in the utilisation of generation infrastructure and electricity network assets. As a result, system integration costs are expected to increase considerably. [Carbon trust 2012] Energy storage technologies, including batteries, have the potential to support future system integration. Determining the value storage brings to the system, and therefore its cost targets, again requires a comprehensive whole systems analysis approach that simulates grid operations with and without energy storage alongside alternative technologies. Recent studies which span the whole of Europe and specifically look at the value of battery storage to offer a whole range of services are lacking. Below we will present some of the results of studies which look at a specific region (in this case Massachusetts and the UK) and/or application (in this case self-consumption). However, the potential, are poorly understood to date.

In the Massachusetts example which was already discussed in previous section and which is illustrated hereafter (see Figure 55) the vast majority of savings from deploying 1,766 MW of energy storage came from reducing the need for peak capacity [DOER MASSCEC 2016]. The simulation results show an opportunity to reduce peak demand in Massachusetts by 908 MW in 2020 when the entire 1,766 MW of energy storage are deployed. That reduction is equal to 9.77% of peak load and would result in $1,093 million USD in savings because it defers capital costs for peaker plants and reduces costs in capacity markets.

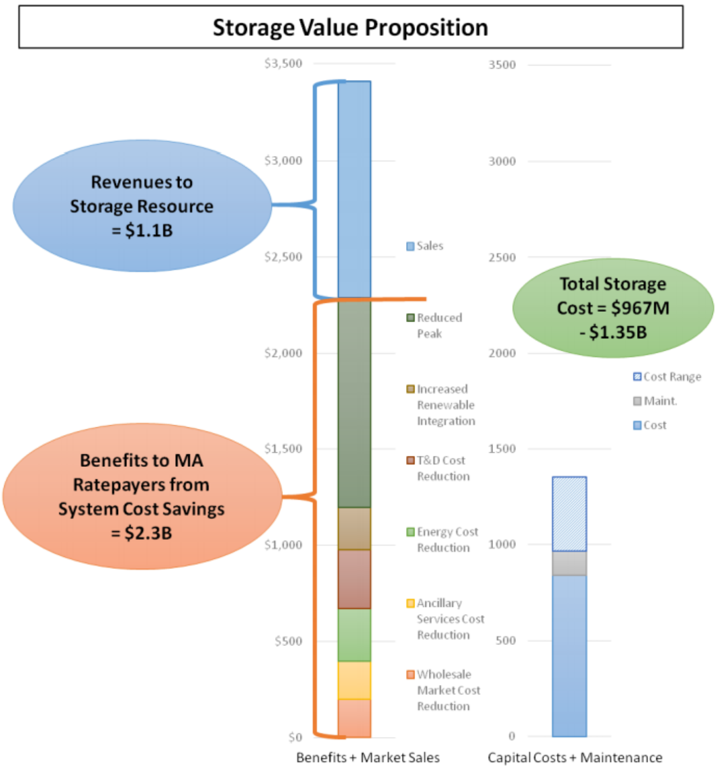


Figure 55: Storage Value Proposition, Massachutusetts State of Charge [DOER MASSCEC 2016]

The Preparatory study on Smart Appliances [VITO 2016a, VITO 2016b] covered most of Europe (EU28), but focused on residential batteries for self-consumption. The study investigated how potential (future) flexibility provided by smart appliances can support the power system in EU28. The optimisation model used determined the optimal utilization of flexibility from each appliance group to minimize the total energy system costs. Batteries are one of the options which was modelled with a specific focus on home batteries. One of the KPIs which is calculated is the *"economic value in terms of total energy system costs"*. This KPI quantifies the *"avoided costs related to the more efficient use of the energy system following the introduction of the flexibility from smart appliances"*. For the home batteries it is assumed that these are not utilized for arbitrage on the energy and reserve markets, but in combination with PV production capacity to store the excess of solar power production. For 2020 the benefits due to the flexibility of batteries range between 72-79 €/year/battery with an average installed capacity of approximately 3.3 kW/7 kWh for each battery. Starting from our battery storage projections for residential self-consumptions of 876 MW in 2020 and 4,080 MW in 2025 (see Table 9), assuming the same average installed capacity of 3.3 kW and assuming that the value of 72-79 €/year/battery would still be applicable in 2025 although higher values could be expected due to the introduction of more VRES, the yearly energy cost savings of using home batteries for self-consumption in Europe could amount to 19-21 million € in 2020 and 89-98 million € in 2025.

Table 10: : Analysis of yearly projected values of home batteries in Europe

	2020	2025
Installed capacity [MW]	876	4,080
Number of home batteries	265,455	1,236,364
Estimated yearly value [M€/year]	19-21€	89-98€

In [Carbon trust 2012] the potential of electricity storage to reduce the costs of electricity generation was also investigated, but this study focused specifically on the future UK energy system. The whole-systems cost minimisation approach of this study identified significant saving opportunities by balancing and aggregating benefits across various use cases, including networks, generation capacity and system operation. The figure below shows that the value of storage increases very significantly in the scenario with increasing contribution of renewable generation throughout the years for the example of distributed storage of 10 GW installed capacity in the UK. This analysis demonstrates that the value of energy storage technologies in energy systems with large contribution of renewable generation may be very significant and would be around 300 £/kW a year in 2030.

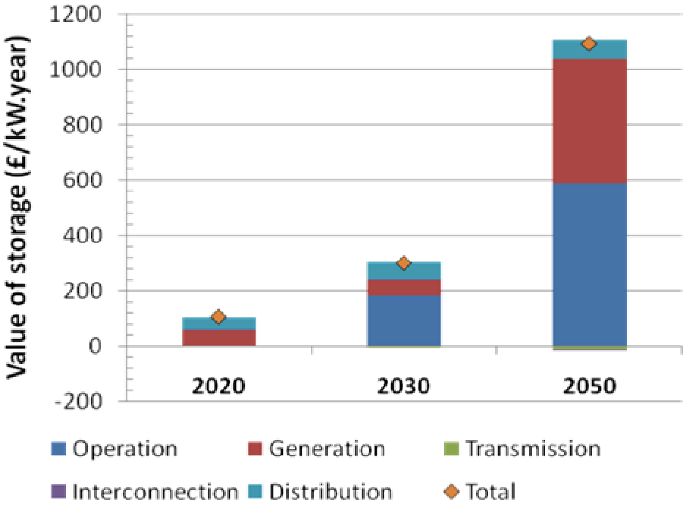
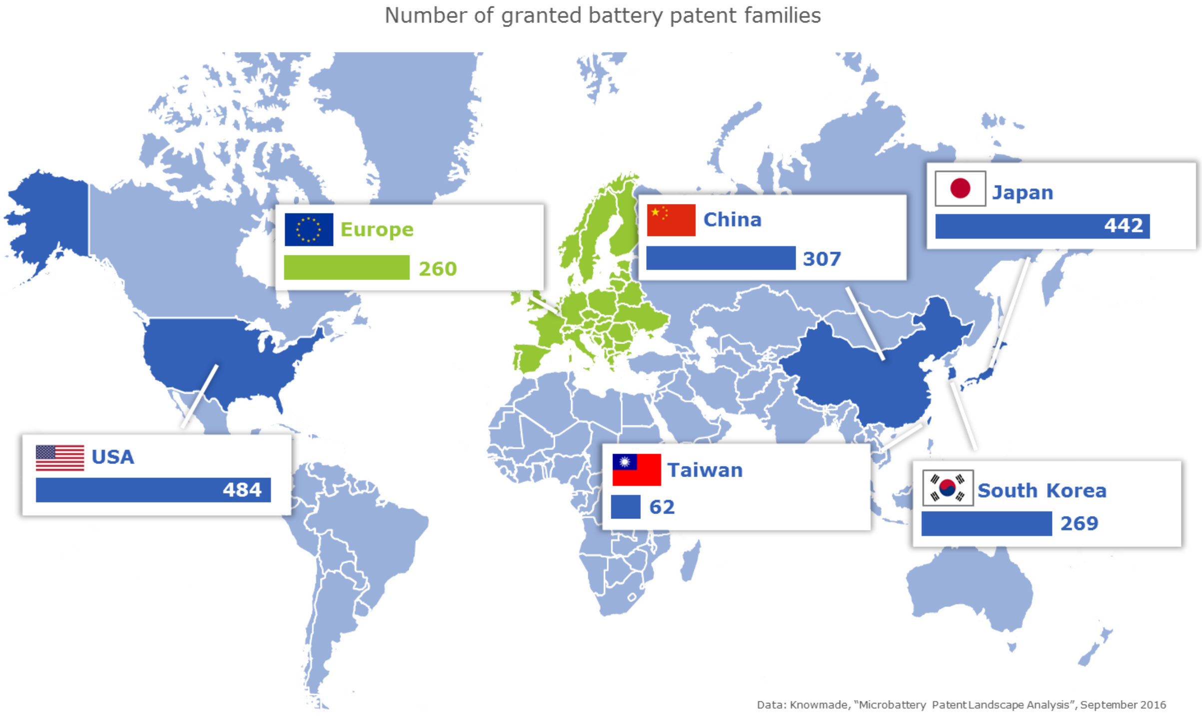


Figure 56: Value of storage in future scenarios in the UK energy system [Carbon trust 2012]

7.2 The EU battery industry

A look at the patent landscape of the global battery industry reveals that Europe is among the key regions with a significant set of know-how. Figure 57 gives an overview of the number of granted battery patent families[39] in the U.S., Europe, China, Taiwan, South Korea and Japan.



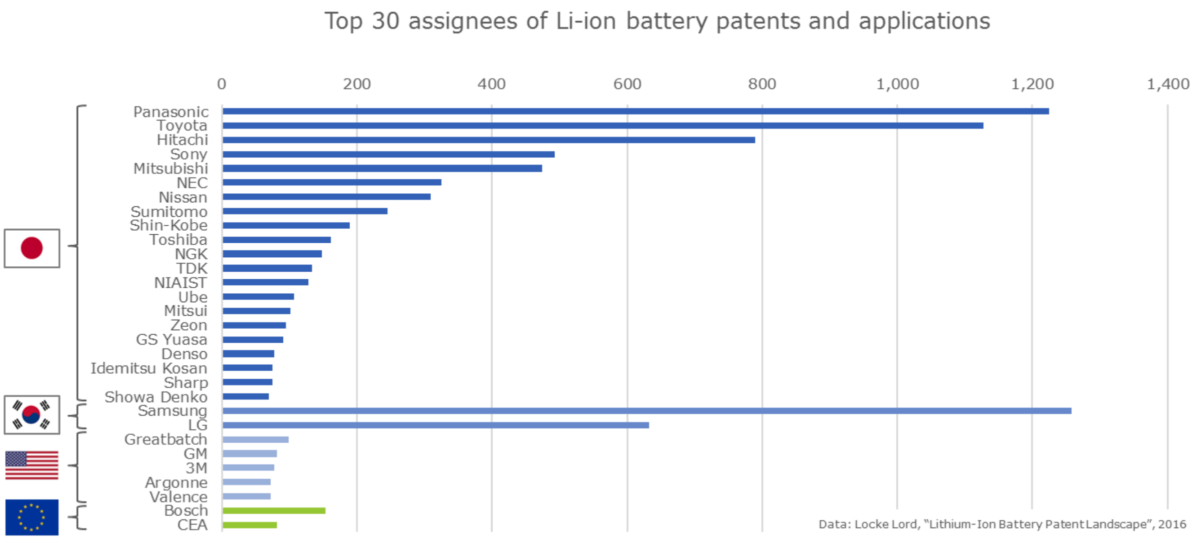
Data: Knowmade, "Microbattery Patent Landscape Analysis", September 2016

Figure 57: Battery patent landscape

However, there are only two European companies among the top 30 assignees of lithium-ion battery patents and applications. These are Germany-based engineering and electronics company Robert Bosch and the France Alternative Energies and Atomic Energy Commission (CEA). The industry is patent-wise strongly dominated by Japanese manufacturers as shown in Figure 58.

---

[39] A patent family is a set of patents filed in multiple countries by a common inventor to protect a single invention.


Top 30 assignees of Li-ion battery patents and applications

Data: Locke Lord, "Lithium-Ion Battery Patent Landscape", 2016

Figure 58: Top 30 manufacturers with Li-ion patents

An overview of the global top export markets and import markets of lithium-ion battery components confirms the minor roles that European countries are playing in the industry today. Figure 59 also portrays the massive flow of battery components from Asia to the U.S. Figure 60 presents the manufacturing capacities of lithium-ion batteries today and in the future. While Japan and South Korea host the majority of global production capacities today, China is on the rise and Tesla's Gigafactory in the U.S. is expected to completely alter the industry's status quo [CEMAC 2016].

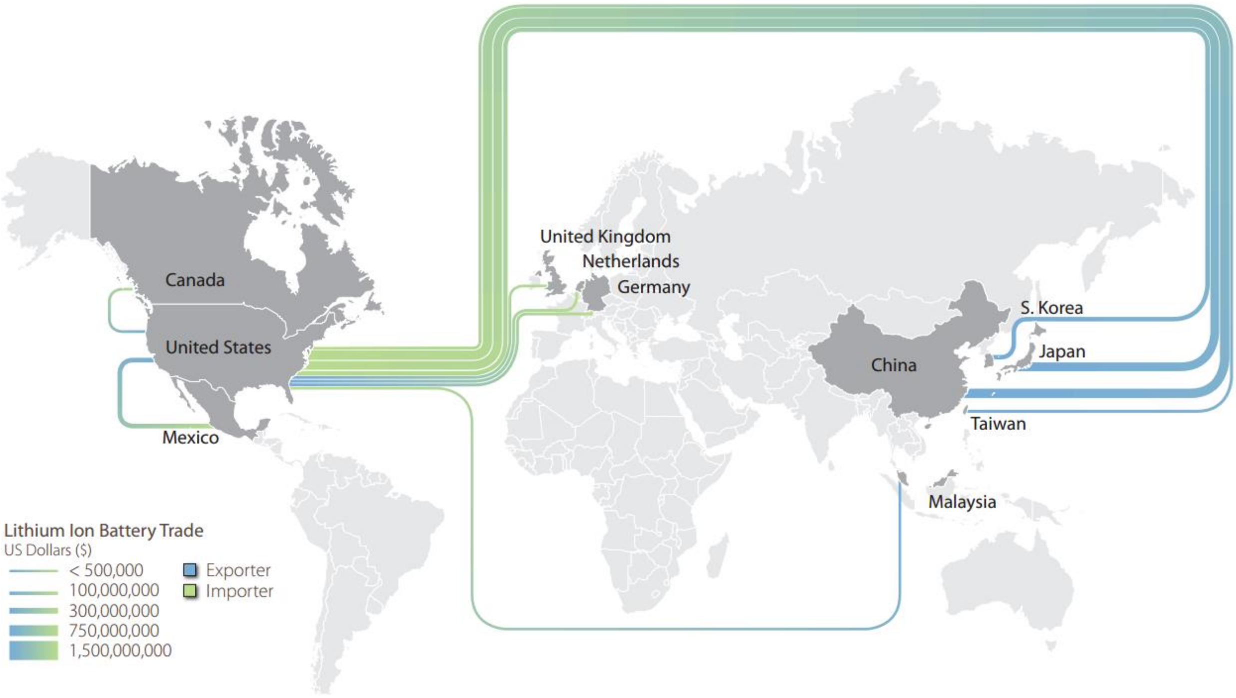


Figure 59: Value of trade in lithium-ion battery components between the top export and import markets, 2012-2014 annual average [CEMAC 2016]

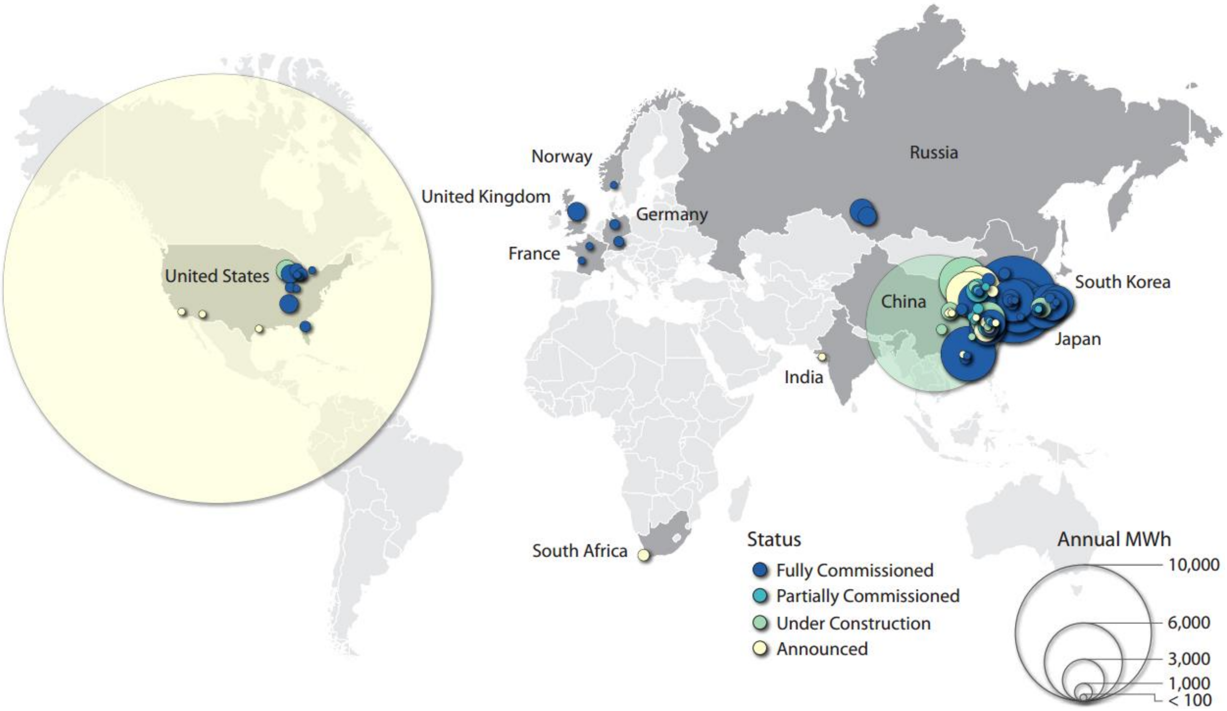


Figure 60: Manufacturing capacity for lithium-ion batteries [CEMAC 2016]

Table 11 lists the manufacturing capacities per country in 2014 including commissioned and under construction factories.

Table 11: Manufacturing capacity for lithium-ion batteries in MWh, 2014 [CEMAC 2016]

China	Korea	Japan	U.S.	EU	Rest
39,010	16,059	11,978	4,970	1,798	2,440

An online survey among experts in the battery industry has been carried out within the BATSTORM project. Two of the questions in this survey addressed the position of the EU in the battery value chain in comparison to the rest of the world. All questions were framed technology-neutral and addressed Europe’s battery industry in general. Figure 61 shows the survey results from the question on the strength of the position of the EU in the global battery value chain (from battery materials to battery cells, battery modules, battery systems, integration of battery systems and finally recycling of batteries). Respondents could rate the position of the EU from non-existent (0) to weak (1), strong (2) and very strong (3). The results show that EU-based companies are perceived strong only in the higher stages of the battery value chain and weak on the raw material and processing level.

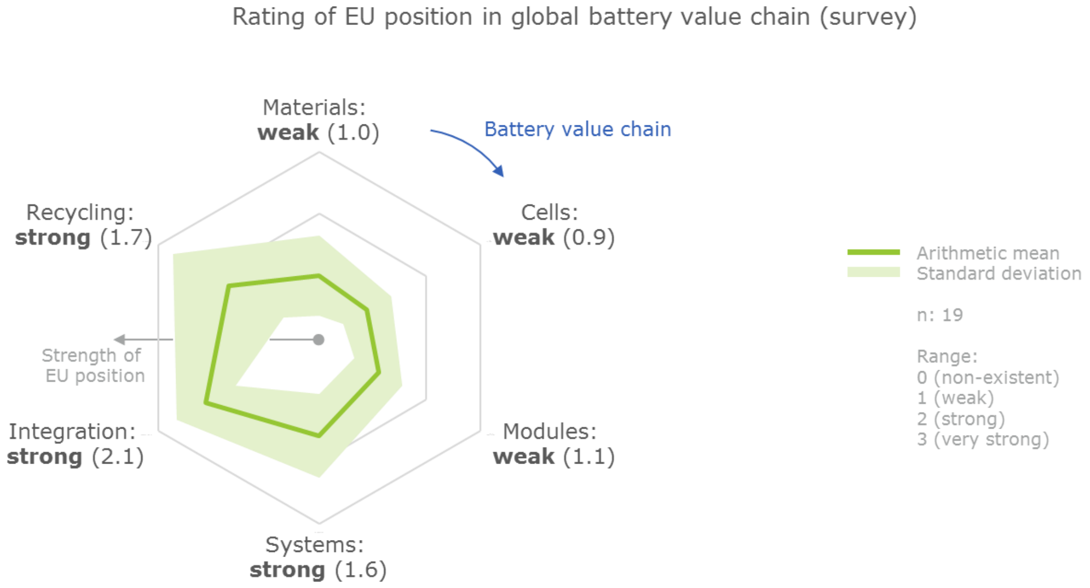


Figure 61: Survey results concerning EU position in global battery value chain

Survey participants agreed that the strongest competition for the European battery industry is based in China, South Korea, Japan and the U.S.. Chinese companies are perceived very strong on the materials level while the South Korean industry is especially strong in manufacturing battery cells and modules. The U.S. hosts strong integrators of battery systems while Japan is quite strong in every stage of the battery value chain. Figure 62 illustrates the results of the second question in our online survey regarding EU position in the value chain, namely respondents were asked to name the strongest competitors.

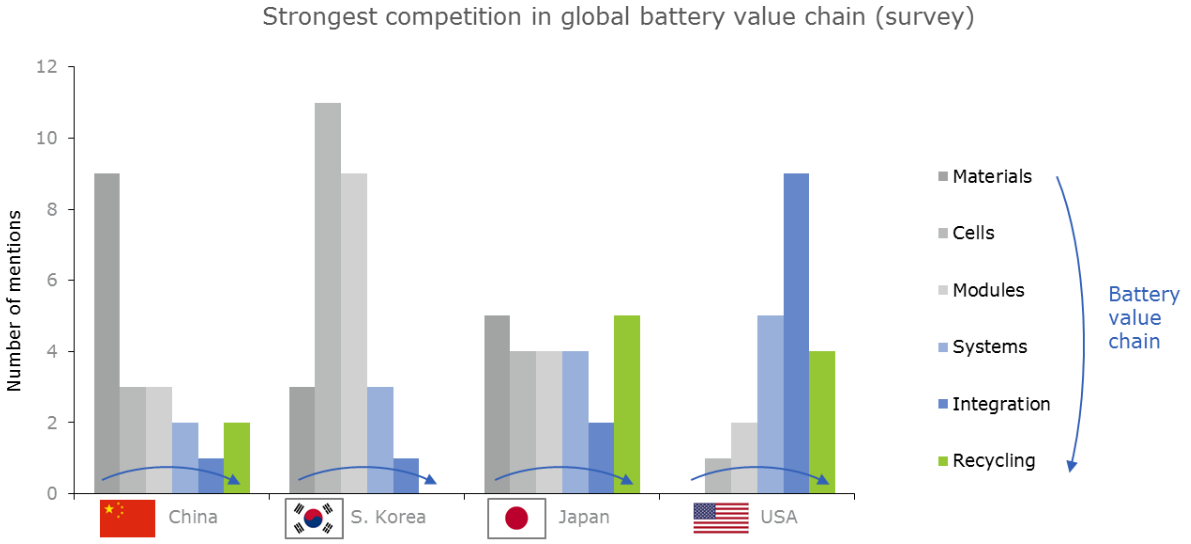


Figure 62: Survey results concerning strongest competition in global battery value chain

The European battery industry is mainly organised within three major industry associations along the battery supply chain:

- EMIRI:
  - Energy Materials Industrial Research Initiative: raw material and advanced materials for batteries.
  - Members: 3M, AGC, ArcelorMittal, BEKAERT, BOSCH, Danish Power Systems, Dow Corning, DSM, H.C.Starck, Heraeus, JRS Micro, Laborelect GDF Suez, Plansee, Saet group, SAFT, Siemens, Solvay, Topsoe Fuel Cell, Umicore, Voestalpine, Sustesco.
- EUROBAT:
  - Association of European Automotive and Industrial Battery Manufacturers: battery cells and packs supply.
  - Members: Moll, Assad, Akom, Banner, EnerSys, Eternity Technologies, Exide Technologies, FIAMM, FZSONICK, Hoppecke, Inci Akü, Istok, Johnson Controls, Midac, Mutlu Akü, Powertech Batteries, ROMBAT, SAFT, Systems Sunlight, TAB, Yuasa, Alpha House, Albertax Technologies, Accuma, Accumalux, Amer-Sil, Battbox, BM Rosendahl, Daramix, ECOBAT Technologies, EL BAT, DEKRA, Entek, Frötek, Glatfelter, Hammond Expanders, Hofmann Power Solution, Hollingsworth & Vose, Hyperdrive Innovation, IKERLAN, MECANDOR, Microporous, MIDTRONICS, Mistui, MTH, NISSAN, Pyrotek, Recyclex, Siemens, SOVEMA, T.B.S. Engineering, Toray, Volta Nano, Water Gremlin Aquila.
- EASE:
  - European Association for Storage of Energy: grid integration of battery storage
  - Members: AES, BASF, BOSCH, CENER, Cobra, Circe, DBE, DNV GL, DTU, EDF, Elia, EnBW, Enel, Engie, FIAMM, Fraunhofer Umsicht, Gaelectric, GasNatural fenosa, GE, GlenDimplex, Highview Power Storage, Hydrogenics, Iberdrola, Johnson Controls, LG Chem, Maxwell, MI Power Systems, Panasonic, PGE, RED Electrica, RWE, S&C, SAFT, Saint-Gobain, Siemens, TDK, Terna, TNO, Uniper.

An overview of the battery supply chain and the associations is given in Figure 63. Besides these three major associations there are several other organisations, which are focusing more on specific technologies or regions within Europe, such as the KLiB in Germany (Competence Network Li-ion Batteries).

Even though the battery recycling industry is not explicitly represented in these associations, there are companies in Europe that are very strong and experienced in this field, e.g. Rockwood or Umicore. According to the survey results there are also competitive companies dealing with recycling in Japan and the U.S.

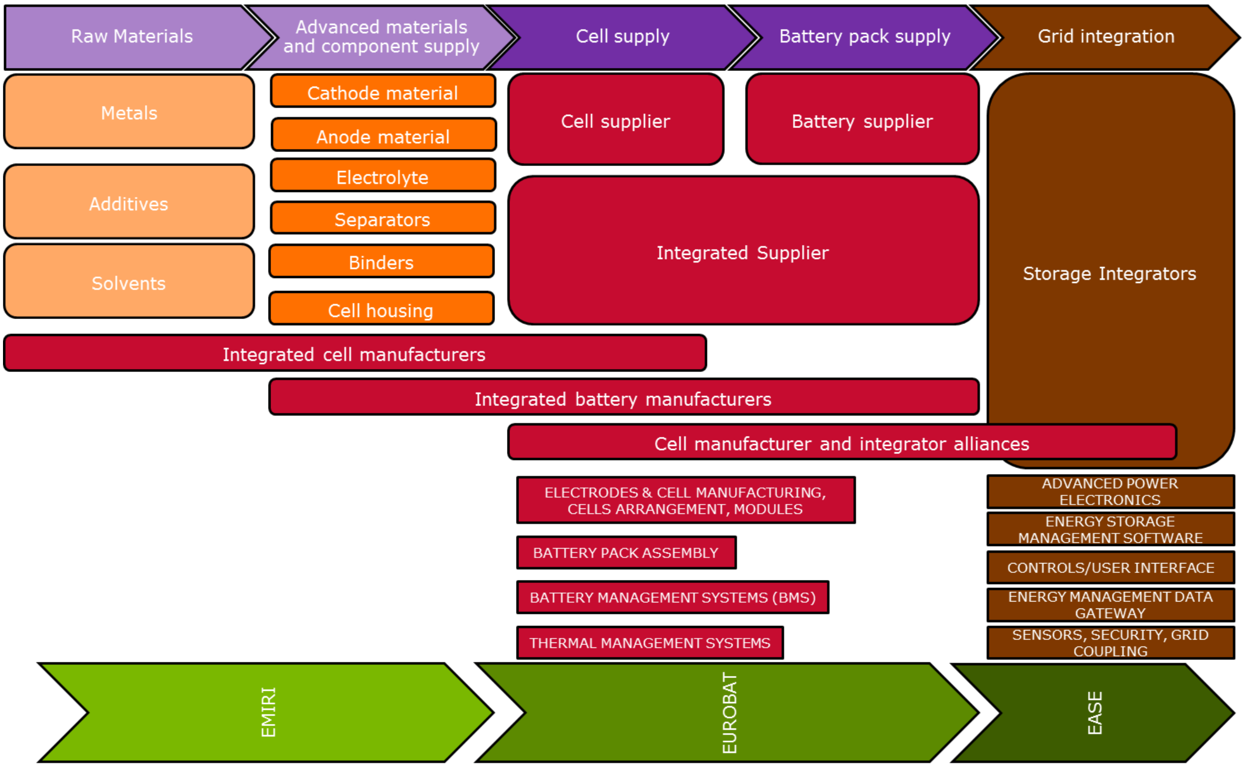


Figure 63: European battery supply chain

Stakeholder workshops have delivered various observations, conclusions and suggestions regarding the EU battery industry. It was stated that large-scale battery cell manufacturing is practically non-existent in Europe. A strong local industry in all parts of the value chain located close to the market would be very beneficial though. There will be a strong increase in demand for batteries from the European automotive industry during the coming years. In order to reduce dependency (on supply from Asia) and increase reliability of supply, a strong local battery industry is important. At the same time sustainability and safety are sensitive subjects of sourcing or disposal of batteries in emerging or developing economies. While Europe is well advanced in battery recycling, processes have not yet achieved cost-effectiveness.
In order to achieve economies of scale and competitiveness, tremendous investments are necessary but the investment climate is perceived as suboptimal. A joint industrial vision and a strong industrial network are missing. An amalgamation of European battery manufacturers may be beneficial and lead to a global leadership role of Europe (‘Airbus model’).

In conclusion, the development of the global value chain for batteries and battery systems over the past years and decades raises the question whether Europe will be competitive, especially in the manufacturing industry. The Li-ion battery supply chain is dominated by manufacturers in Asia. During the Li-ion era some argue it may be best to focus on system development, integration of battery systems and recycling while performing research and innovation on material level for a potential new generation of batteries. Many experts have suggested that Europe could become a leading developer and manufacturer of new generation batteries with advanced materials. However, others argue that Li-ion technology will be dominant for some decades and the EU must become a bigger player already in this technology – especially in order to enable and secure the (electric) automotive industry.

8 Conclusions

8.1 Role of battery storage in the energy system

Today, grid connected battery storage plays a modest role in the current global energy system (approximately 1.2 GW battery capacity installed within a total of 150 GW storage capacity). However, this capacity has been growing rapidly and there are valid reasons to expect that the role of such batteries will continue to grow.

The value of energy storage for the energy system lies in the application these can provide for the system. According to the International Energy Agency the true asset of BESS lies in their modularity, controllability and responsiveness as no other asset in the power sector can combine these characteristics [IEA 2014b]. While there are some differences in the characteristics among the various battery technologies, when considering this fundamental value to the energy system, the similarities may be considered greater than the difference.

Many different studies have identified the broad range of applications batteries can provide to the energy system. Figure 64 gives an overview of potential applications.

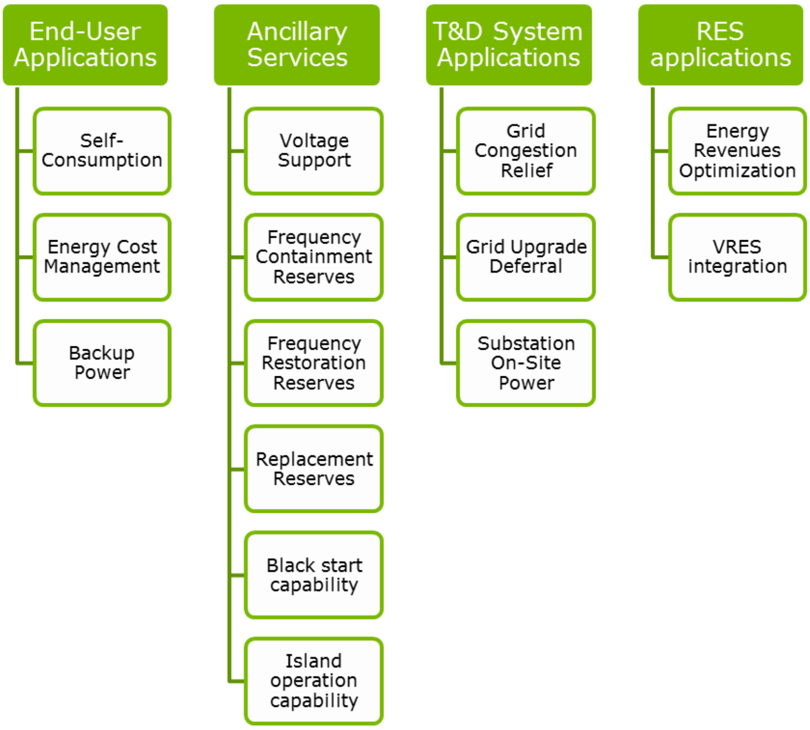


Figure 64: Potential applications for batteries in the (future) EU energy system

Apart from the USA and Japan - where installed grid connected battery capacity is significantly greater - within the European Union, grid connected battery capacity is concentrated in some Western European countries (primarily Germany, Italy and the UK), while there are very few of such systems in Eastern Europe.

8.2 Promising business models for battery storage

From a set of case studies, some existing business models for battery storage are apparent. These provide a valuable starting point for contemplating how the installed battery storage capacity is likely to grow in the foreseeable future:

- Solar Self Consumption and Aggregation at the Residential Level in Germany, with typically privately owned 2 – 10 kWh Li-Ion systems, while these have the potential to also be used for aggregated dispatchable power operation;
- Frequency reserve services in Northern Ireland (UK), where 1 – 100 MW systems with various technologies are used to provide system services on a commercial basis in the ancillary services market;
- Grid upgrade deferral in Italy, where 1 – 20 MW battery systems are used to alleviate grid congestions in areas with increasing solar PV and wind energy penetration as well as a weak power grid, with a typical break-even cost around 260 € / kWh installed capacity;
- Variable Renewable Energy Service Optimization in Italy, comparable battery systems are used as in the previous case to optimise the value of generated renewable energy, with a typical break-even cost around 360 € / kWh installed capacity.

8.3 Battery storage and competing technologies

Battery costs, particularly Lithium-ion, have demonstrated a significant cost reduction over recent years. The reductions have mainly been driven by economies of scale and continued improvements of existing technologies. With developments in Li-ion technology and related technologies (LiS, Na-ion…) as well as increasing scale at which these technologies are applied, there is a good basis to expect continued cost evolution over the next decades. This provides a basis for growing installed capacity of batteries in these various applications.

On the other hand there are a range of competing technologies (Figure 65) that can offer services similar to those of battery storage systems at competitive cost levels. The growth potential for battery storage systems will depend on their future cost competitiveness relative to the evolving cost level of these competing technologies.

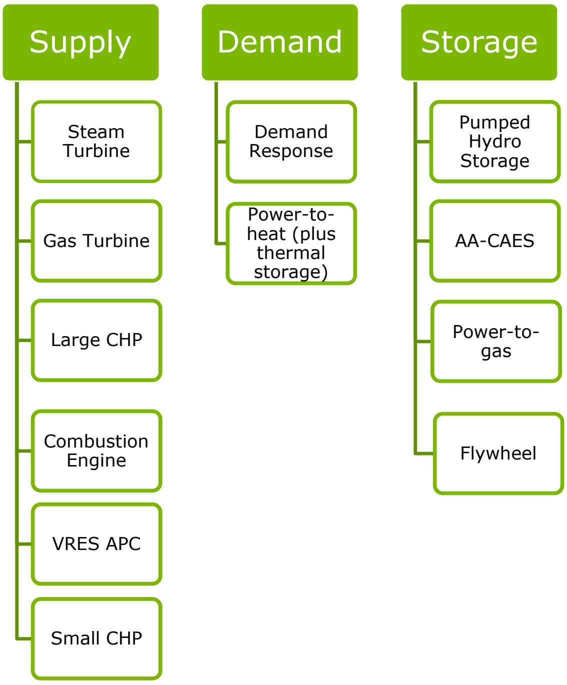


Figure 65: Flexibility options in the energy system aside from batteries

8.4 Battery storage deployment scenarios

Literature research showed that most existing studies focus on the role of large scale storage of electrical energy at transmission grid level, without considering the other applications (such as distribution grid congestion or behind the meter storage at users). Therefore, a preliminary outlook for battery capacity development up to 2020 and 2025 was prepared based on (a) listing the main areas of application of these systems, (b) identifying the key drivers for each of these applications and considering the expected growth of these drivers and (c) estimating the potential of battery storage for each of these applications taking into account the respective drivers. The main results from this analysis are summarised in Table 12: a total estimated capacity of between 7,600 MW and 9,800 MW to be reached by 2020 and between 11,500 MW and 14,500 MW in 2025.

The literature reviewed pointed to installed battery capacities by 2050 in the range of 3 to 130 GW, due to the very high levels of RES penetration. Therefore, the bigger part of this capacity is likely to materialise in the period beyond 2025.

Clearly, this is a preliminary development scenario that is to be further developed in the following 12 months of this study, as more information will be gathered on the growth potential as well as for specific drivers and hurdles.

Table 12: Summary of battery storage applications projections

Application	Main growth driver	Installed BESS capacity in 2016:	Projection BESS capacity in 2020	Projection BESS capacity in 2025
Self-consumption	Residential PV systems installed, grid parity of PV systems	144 MW	876 MW	4,080 MW
Energy cost management	Differential between peak and off-peak pricing	34 MW	102 MW	187 MW
Backup power	Expansion of telecommunication and other relevant industries System Average Interruption Duration (SAIDI)	5,000 MW	5260 MW	5530 MW
Voltage Support	RES penetration, system need and development of conventional providers	17 MW	Min 17 MW[40]	Min 17 MW
Enhanced Frequency Response (EFR)	System inertia	0 MW	23-113 MW	23-500 MW
Frequency Containment Reserves (FCR)	RES penetration, system need and development of conventional providers	88 MW	300-1,500MW	300-1,500 MW
Automatic Frequency Restoration Reserve (aFRR)	RES penetration, system need and development of conventional providers		924-1,848 MW	1,008-2,016 MW
Manual Frequency Restoration Reserve (mFRR)	RES penetration, system need and development of conventional providers		0 MW	0 MW
Replacement Reserves (RR)	RES penetration, system need and development of conventional providers		0 MW	0 MW
Black start capability	Regulatory requirements to provide black start from the distribution grid / with batteries	2 MW	Min 2 MW[41]	Min 2 MW
Island Operation Capability		10 MW	60 MW	100 MW

---

[40] Assuming that the installed battery capacity will remain in the grid

[41] Assuming that the installed battery capacity will remain in the grid

Application	Main growth driver	Installed BESS capacity in 2016:	Projection BESS capacity in 2020	Projection BESS capacity in 2025
Grid congestion relief **Grid upgrade deferral**	RES penetration (and costs of alternative solutions)	15 MW 9 MW	30 MW	400 MW
Substation on-site power	Grid expansion with increasing numbers of substations	0.5 MW	2.4 MW	4.2 MW
Energy revenues optimisation **VRES integration**	Renewable energy curtailment	12 MW	14 MW	20 MW
SUM		5,320 MW	7,600 – 9,800 MW	11,500 – 14,500 MW

8.5 Socio-economic impact of batteries

The **economic impacts** expected from battery storage deployment in Europe are summarized as follows:

- European battery sales will increase from USD 60 million in 2014 to USD 5 billion until 2023 for utility-scale applications. [INSIGHT_E 2014, IRENA 2015a];
- The battery market for behind-the-meter applications currently exceeds the market volume of batteries for utility-scale applications and adds up to 2.1 billion € in 2015. The market is expected to grow and will reach a market volume of approximately 5 billion € in 2025. [AGORA 2014, RWTH 2016];
- Growing demand of battery cells will create the need of increasing production capacity in Europe; thus creating 4,000 jobs directly or indirectly linked to cell production. [NPE 2016];
- Newly established cell production capacities and overall growing demand of battery systems will foster and strengthen all industries along the battery storage value chain leading to up to 50,000 additional jobs. [REA 2016, KEMA 2010].

Regarding **environmental impacts**, overall the use of battery storage will enable an increase of the use of renewables in the European electricity grid. This would reduce the need and dependency on fossil energy sources and through this reduce GHG emissions related to fossil energy production. Several studies have performed detailed LCA studies, comparing production as well as use of batteries. Overall these studies provide positive results in the field of primary fossil energy reduction and GHG emissions, when batteries are compared to current situation or alternative technologies. The results of these studies however depend a lot on the specific type of energy source replaced, the exact use of the battery and the battery technology applied. General conclusions are therefore more difficult to draw. Cost-effective reuse and recycling strategies should be further studied for all battery technologies, including lithium ion.

In relation to the **social dimension**, energy storage can reduce the cost of energy directly at the customer meter by allowing more solar self-consumption or lower electric bills by capping demand charges or doing energy arbitrage. However, the true savings appear at the system level with the following factors:

- Reduced Peak Demand: energy storage can defer capital costs in peaking capacity and reduce the costs of procuring capacity;
- Reduced Costs of Ancillary Services: Overall reduction of the costs of ancillary services by using energy storage;
- Energy Cost Reduction: energy storage is used to redistribute cheap energy during peak demand periods, limiting the need to costly generators;
- T&D Cost Reduction: energy storage is used to defer investments in costly infrastructure upgrades.

Assessing the **EU industry position and potential**, it was shown that in the market of lithium-ion battery components EU countries are currently playing a minor role, especially in manufacturing. EU-based companies are perceived strong only in the higher stages of the battery value chain and weak on the raw material and processing level. In the field of recycling there are companies in Europe that are very strong and experienced in this field, e.g. Rockwood or Umicore. While Europe is well advanced in battery recycling, processes have not yet reached cost-effectiveness.

The development of the global value chain for batteries and battery systems over the past years and decades raises the question whether Europe will be competitive, especially in the cell production industry. Some argue it may be best to focus on system development, integration of battery systems and recycling while performing research and innovation on material level for a potential new generation of batteries. Many experts have suggested that Europe could become a leading developer and manufacturer of new generation batteries with advanced materials. However, others argue that Li-ion technology will be dominant for some decades and the EU must become a bigger player already in this technology – especially in order to enable and secure the (electric) automotive industry.

References

- [50Hertz Transmission GmbH et al. 2013] "Netzentwicklungsplanstrom 2013. erster Entwurf der Übertragungsnetzbetreiber", 50Hertz Transmission GmbH, Amprion GmbH, TenneT TSO GmbH, TransnetBW GmbH, 2013.

- [AEEG 2013a] „Balancing the needs of investors whilst empowering network users", AEEG, ICER – GO15 joint workshop, 18 April 2013. Available online: http://www.icer-regulators.net/portal/page/portal/ICER_HOME/activities/ICER_Events/ICER_GO15_Workshop/Session1_3_LoSchiavo_def.pdf

- [AEEG 2013b] "Prime disposizioni relative ai sistemi di accumulo –orientamenti", AEEG, 19 December 2013. Available online: http://www.autorita.energia.it/allegati/docs/13/613-13.pdf

- [AES 2016] Presentation Grid plus storage workshop, AES, 15 March 2016. "", Available online: http://www.gridplusstorage.eu/workshops/8-workshop-9-ireland-uk

- [Agora 2014] "Stromspeicher in der Energiewende. Untersuchung zum Bedarf an neuen Stromspeichern in Deutschland für den Erzeugungsausgleich, Systemdienstleistungen und im Verteilnetz", Agora Energiewende, September 2014. Available online: https://www.agora-energiewende.de/fileadmin/downloads/publikationen/Studien/Speicher_in_der_Energiewende/Agora_Speicherstudie_Web.pdf

- [BATSTORM D5] "Technical analysis of projects" BATSTORM deliverable D5, 13 April 2016

- [BATSTORM D8] "Initial Implementation Plan 2016-2018", BATSTORM deliverable D8, 20 June 2016.

- [BET 2011] "Kapazitätsmarkt. Rahmenbedingungen, Notwendigkeit und Eckpunkte einer Ausgestaltung", BET, 2011.

- [BIP 2013] „Electrochemical Energy Storage Systems in the Italian Power Industry", Business Integration Partners, November 2013.

- [Blechinger 2014] "Assessment of the global potential for renewable energy storage systems on small islands", P. Blechinger, R. Seguin, C. Cader, P. Bertheau, Ch. Breyer, 2014. Available online: http://www.sciencedirect.com/science/article/pii/S187661021400201X

- [Bloomberg 2016] "Here's How Electric Cars Will Cause the Next Oil Crisis ", Bloomberg, February 2016. Available online: http://www.bloomberg.com/features/2016-ev-oil-crisis/

- [BMWi 2014] "Moderne Verteilernetze für Deutschland (Verteilernetzstudie)", Germany Federal Ministry of Economics and Technology, September 2014. Available online: http://www.bmwi.de/BMWi/Redaktion/PDF/Publikationen/Studien/verteilernetzstudie-englisch,property=pdf,bereich=bmwi2012,sprache=de,rwb=true.pdf

- [BNetzA 2016] "Monitoring report 2015", Bundesnetzagentur, March 2016. Available online: http://www.bundesnetzagentur.de/SharedDocs/Downloads/EN/BNetzA/PressSection/ReportsPublications/2015/Monitoring_Report_2015_Korr.pdf;jsessionid=BF7CDF343DC98AAB86B635C64CC3048B?__blob=publicationFile&v=4

- [Bussar et al. 2014] Bussar, Christian; Moos, Melchior; Alvarez, Ricardo; Wolf, Philipp; Thien, Tjark; Chen, Hengsi et al. "Optimal Allocation and Capacity of Energy Storage Systems in a Future European Power System with 100% Renewable Energy Generation" Energy Procedia 46, 2014. DOI: 10.1016/j.egypro.2014.01.156.

- [Carbon trust 2012] Strategic Assessment of the Role and Value of Energy Storage Systems in the UK Low Carbon Energy Future, G. Strbac et al, Imperial College, 2012

- [Carbon trust 2016] "Can storage help reduce the cost of a future UK electricity system?", Carbon Trust, Imperial college, February 2016. Available online: http://www.carbontrust.com/media/672486/energy-storage-report.pdf
- [Castillo et al 2014] Anya Castillo, Dennice F. Gayme, "Grid-scale energy storage applications in renewable energy integration: A survey", Energy Conversion and Management, Volume 87, November 2014, Pages 885-894, ISSN 0196-8904. Available online: http://dx.doi.org/10.1016/j.enconman.2014.07.063
- [CBS 2016] „Elektriciteit en warmte; productie en inzet naar energiedrager", Centraal bureau voor de Statistiek, April 2016. Available online: http://statline.cbs.nl/Statweb/publication/?DM=SLNL&PA=80030NED&D1=1,3&D2=0&D3=a&D4=7-16&HDR=T&STB=G1,G2,G3&CHARTTYPE=1&VW=T
- [CEMAC 2016] "2015 Research Highlights", Clean Energy Manufacturing Analysis Center, http://www.nrel.gov/docs/fy16osti/65312.pdf
- [CONSENTEC, Fraunhofer IWES 2013] "Kostenoptimaler Ausbau der Erneuerbaren Energien in Deutschland. Ein Vergleich möglicher Strategien für den Ausbau von Wind- und Solarenergie in Deutschland bis 2033", CONSENTEC, Fraunhofer IWES, 2013.
- [CONSENTEC, IAEW 2011] "Bewertung der Flexibilitäten von Stromerzeugungs- und KWK-Anlagen", CONSENTEC, IAEW, 2011.
- [CONSENTEC, r2b energy consulting 2010] "Voraussetzungen einer optimalen Integration erneuerbarer Energien in das Stromversorgungssystem", Study commissioned by des Bundesministeriums für Wirtschaft und Technologie (BMWi), CONSENTEC, r2b energy consulting, 2010.
- [Czisch 2005] "Szenarien zur zukünftigen Stromversorgung. Kostenoptimierte Variationen zur Versorgung Europas und seiner Nachbarn mit Strom aus erneuerbaren Energien", Czisch G., . Dissertation, Universität Kassel, Institut für Elektrische Energietechnik/Rationelle Energiewandlung, 2005.
- [D.LGS 28/11] Decreto Legislativo 3 marzo 2011 n. 28, Attuazione della direttiva 2009/28/CE sulla promozione dell'uso dell'energia da fonti rinnovabili, recante modifica e successiva abrogazione delle direttive 2001/77/CE e 2003/30/CE (art17). Available online: http://unmig.sviluppoeconomico.gov.it/unmig/norme/28dlg11.htm
- [D.LGS 93/11] Decreto Legislativo 1 giugno 2011, n. 93, Attuazione delle direttive 2009/72/CE, 2009/73/CE e 2008/92/CE relative a norme comuni per il mercato interno dell'energia elettrica, del gas naturale e ad una procedura comunitaria sulla trasparenza dei prezzi al consumatore finale industriale di gas e di energia elettrica, nonche' abrogazione delle direttive 2003/54/CE e 2003/55/CE (art. 36 comma 4). Available online: http://www.altalex.com/documents/leggi/2011/08/30/decreto-legislativo-01-06-2011-n-93
- [DEL.281/2012/R/EFR] Deliberazione 5 Luglio 2012, 281/2012/R/Efr, Revisione del servizio di dispacciamento dell'energia elettrica per le unità di produzione di energia elettrica alimentate da fonti rinnovabili non programmabili. Available online: http://www.autorita.energia.it/allegati/docs/12/281-12.pdf
- [Dena 2014] "Ancillary Services Study 2030. Security and reliability of a power supply with a high percentage of renewable energy", Dena, 2014. Available online: http://www.dena.de/fileadmin/user_upload/Projekte/Energiesysteme/Dokumente/dena_Ancillary_Services_Study_2030.pdf
- [Dena, IAEW 2012] "Integration der erneuerbaren Energien in den deutsch-europäischen Strommarkt", Dena - IAEW, 2012.
- [Deutsche Bank 2015] "F.I.T.T. for investors - Crossing the Chasm", Deutsche Bank, 27 February 2015. Available online: https://www.db.com/cr/en/docs/solar_report_full_length.pdf

- [Directive 2009/28/EC] “Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC”, of 23 April 2009.
- [DLR, et al. 2012] "Langfristszenarien und Strategien für den Ausbau der erneuerbaren Energien in Deutschland bei Berücksichtigung der Entwicklung in Europa und global. Schlussbericht", DLR, Fraunhofer IWES, IfnE, 2012.
- [DNV GL 2014] “Integration of Renewable Energy in Europe”, DNV GL, June 2014. Available online: https://ec.europa.eu/energy/sites/ener/files/documents/201406_report_renewables_integration_europe.pdf
- [DoE 2016] “ U.S. Department of Energy (DoE) Global Energy Storage Database”, DoE, downloaded April 2016. Available online: http://www.energystorageexchange.org/
- [DOER MASSCEC 2016] “State of Charge”, Department of Energy Resources and Massachusetts Clean Energy Center, 2016. Available online: http://www.mass.gov/eea/docs/doer/state-of-charge-report.pdf
- [Droste-Franke 2012] “Balancing renewable electricity. Energy storage, demand side management, and network extension from an interdisciplinary perspective”, Droste-Franke B., Ethics of science and technology assessment, 2012.
- [DS3 2014] “Delivering a Secure, Sustainable Electricity System (DS3)”, Programme Overview, 2014.
- [EC 2015a] “Towards an Integrated Strategic Energy Technology (SET) Plan: Accelerating the European Energy System Transformation”, EC, September 2015. Available online: https://setis.ec.europa.eu/system/files/Communication_SET-Plan_15_Sept_2015.pdf
- [EC 2015b] “The European Union leading in renewables – COP21 brochure”, 2015, Avalable online: http://ec.europa.eu/energy/sites/ener/files/documents/cop21-brochure-web.pdf
- [EC 2016a] “Issue paper No7 – Become competitive in the global battery sector to drive e-mobility forward”, EC, 19 April 2016 – version 3.0. Available online: https://setis.ec.europa.eu/system/files/action7_issues_paper.pdf.
- [EC 2016b] “Establishing a guideline on electricity transmission system operation‟, EC, draft, approved by member states in May 2016, Available online: https://ec.europa.eu/energy/sites/ener/files/documents/SystemOperationGuideline%20final%28provisional%2904052016.pdf.
- [Eclarion 2011] “Integration of electricity from renewables to the electricity grid and to the electricity market”, Eclareon, RES INTEGRATION, National report: Italy, 2011. Available online: http://www.eclareon.com/sites/default/files/italy_-_res_integration_national_study_nreap.pdf
- [ECN 2015] “Nationale Energieverkenning 2015, ECN, 2015. Available online: https://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-O--15-03.
- [Ecofys 2014] “Flexibility options in electricity systems”. Ecofys, 10 March 2014, Available online: http://www.ecofys.com/files/files/ecofys-eci-2014-flexibility-options-in-electricity-systems.pdf
- [Ecofys 2016] “Value of Congestion Management report”, (“Waarde van congestiemanagment”), Ecofys, 2016.
- [FfE 2016] “Verbundforschungsvorhaben Merit Order der Energiespeicherung im Jahr 2030 – Teil 1: Hauptbericht‟, FfE, May 2016. Available online: https://www.ffe.de/images/stories/Themen/414_MOS/20160531_MOS_Hauptbericht.pdf
- [EFET 2014] “Italian power market: towards the achievement of the EU Target Mode‟l, EFET position paper, October 2014. Available online:

http://www.efet.org/Cms_Data/Contents/EFET/Folders/Documents/EnergyMarkets/ElectPosPapers/NatRegLevel/~contents/HT72W446NHQ5FPGH/EFET-position-paper-Italian-power-market.pdf.

- [EIA 2012] "Annual Energy Outlook 2012", U.S. Energy Information Administration, 2012. Available online: https://www.eia.gov/todayinenergy/detail.cfm?id=6930
- [Eirgrid 2015] "Ancillary Services Statement of Payments and Charges", Eirgrid, August 2015. Available online: http://www.eirgridgroup.com/site-files/library/EirGrid/AncillaryServicesStatementOfPaymentsAndCharges2015_2016.pdf
- [Elia 2016] "Studie over de nood aan 'adequacy' en aan flexibiliteit in het Belgische elektriciteitssysteem", Elia, April 2016. Available online: http://www.elia.be/~/media/files/Elia/publications-2/studies/160422_ELIA_AdequacyReport_2017-2027_NL.pdf
- [ENEL 2015] "Enel Distribuzione activities and Real-Time simulations experience for Smart-Grids", ENEL, RT15 Regional User Group Events, Berkeley USA, May 2015.
- [Energy and Environmental Science 2015] "Large-scale electricity storage utilizing reversible solide oxide cells combined with underground storage of CO_2 and CH_4".
- [Energy Storage News 2016] "AES unveils 10 MW Advancion Energy Storage Array in Netherlands", Energy Storage News, February 2016. Available online: http://energystorage.cleantechnology-business-review.com/news/aes-unveils-10-mw-advancion-energy-storage-array-in-netherlands-180216-4814870
- [Enexis 2015] "Smart Storage, Enexis, 2015. Available online: https://www.enexisinnovatie.nl/wp-content/uploads/2015/12/folder-smart-storage-etten-leur.pdf
- [ENI 2016] "Renewable energy in Italy", ENI, February 2016. Available online: http://www.eniscuola.net/en/2016/02/24/renewable-energy-in-italy/
- [ENTSO-E 2012] "Operational reserve ad hoc team report final version", ENTSO-E, May 2012. Available online: https://www.ENTSO-E.eu/fileadmin/user_upload/_library/resources/LCFR/2012-06-14_SOC-AhT-OR_Report_final_V9-3.pdf
- [ENTSO-E 2013] "Network Code on Load-Frequency Control and Reserves", ENTSO-E, June 2013. Available online: https://www.ENTSO-E.eu/fileadmin/user_upload/_library/resources/LCFR/130628-NC_LFCR-Issue1.pdf
- [ENTSO-E 2015a] "TYNDP 2016 Scenario Development Report", ENTSO-E, 3 November 2015. Available online: https://www.ENTSO-E.eu/Documents/TYNDP%20documents/TYNDP%202016/rgips/TYNDP2016%20Scenario%20Development%20Report%20-%20Final.pdf
- [ENTSO-E 2015b] "Statistical Factsheet 2014", ENTSO-E, 27 April 2015. Available online: https://www.ENTSO-E.eu/Documents/Publications/Statistics/Factsheet/ENTSO-E_sfs2014_web.pdf
- [ENTSO-E 2015c] "Scenario Outlook & Adequacy Forecast", ENTSO-E, June 2015. Available online: https://www.entsoe.eu/Documents/SDC%20documents/SOAF/150630_SOAF_2015_publication_wcover.pdf
- [ENTSO-E 2016] "Impact of merit order activation of automatic Frequency Restoration Reserves and Harmonised full activation times", Entso-E, February 2016.
- [EPRI 2010] "Electricity Energy Storage Technology Options - A Primer on Applications, Costs & Benefits", EPRI, 2010. Available online: http://www.epri.com/abstracts/pages/ProductAbstract.aspx?productId=000000000001022261
- [EPRI 2016] "Ensuring a Clean Grid—Batteries Not Excluded", Chris Warren, Epri, 18 January 2016. Available online: http://eprijournal.com/ensuring-a-clean-grid-batteries-not-excluded/
- [EUNOMIA 2016] „Investing in UK Electricity Storage", Eunomia, January 2016. Available online: http://www.eunomia.co.uk/free-download/?fdpid=3443

- [Eurelectric 2013] „Power distribution in Europe, Facts & Figures", eurelectric, 2013. Available online: http://www.eurelectric.org/media/113155/dso_report-web_final-2013-030-0764-01-e.pdf
- [EUROBAT 2016] "Battery energy storage in the EU: Barriers, opportunities, services and benefits", Eurobat, 2016
- [EWI 2012] "Untersuchungen zu einem zukunftsfähigen Strommarktdesign", EWI, 2012.
- [EWI 2013] "Trendstudie Strom 2022. Belastungstest für die Energiewende", EWI, 2013.
- [EWI, EEFA 2008] "Energiewirtschaftliches Gesamtkonzept 2030", EWI, EEFA, 2008.
- [EWI, energynautics 2011] "Roadmap 2050 - a closer look. Cost-efficient RES-E penetration and the role of grid extensions", EWI, energynautics, Final Report, 2011.
- [Fraunhofer 2014] "Optimized pathways towards ambitious climate protection in the European electricity system. EU Long-term scenarios 2050 II", Fraunhofer Institute for Systems and Innovation Research ISI, September 2014. Available online: http://www.isi.fraunhofer.de/isi-wAssets/docs/x/en/projects/Optimized-pathways-final.pdf
- [Fraunhofer 2015a], "Produkt-Roadmap Stationäre Energiespeicher 2030", Fraunhofer-Institut für System- und Innovationsforschung ISI, December 2015. Available online: http://www.isi.fraunhofer.de/isi-wAssets/docs/t/de/publikationen/PRM-SES.pdf
- [Fraunhofer 2015b], "Gesamt-Roadmap Stationäre Energiespeicher 2030", Fraunhofer-Institut für System- und Innovationsforschung ISI, December 2015. Available online: http://www.isi.fraunhofer.de/isi-wAssets/docs/t/de/publikationen/GRM-SES.pdf
- [Fraunhofer ISE 2012] "100 % erneuerbare Energien für Strom und Wärme in Deutschland", Fraunhofer ISE, 2012.
- [Fraunhofer ISI 2011] "Tangible ways towards climate protection in the European Union (EU Long-term scenarios 2050)", Fraunhofer ISI, 2011.
- [Fraunhofer ISI 2014] "EU long Term Scenario 2050 II," Fraunhofer Institute for Systems and Innovation Research ISI, Karlsruhe, 2014.
- [Fraunhofer IWES et al. 2014] "ROADMAP SPEICHER. Bestimmung des Speicherbedarfs in Deutschland im europäischen Kontext und Ableitung von technisch-ökonomischen sowie rechtlichen Handlungsempfehlungen für die Speicherförderung", Fraunhofer IWES, IAEW RWTH Aachen, Stiftung Umweltenergierecht, 2014.
- [Fraunhofer UMSICHT, Fraunhofer IOSB/AST 2013] "Modellbasierte, regional aufgelöste Analyse des Bedarfs an netzgekoppelten elektrischen Energiespeichern zum Ausgleich fluktuierender Energien", Fraunhofer UMSICHT, Fraunhofer IOSB/AST, 2013).
- [Fraunhofer UMSICHT, Fraunhofer IWES 2014] "Metastudie Energiespeicher. Abschlussbericht.", Fraunhofer, 2014.
- [Frontier economics, swissQuant 2013] "Bewertung von Pumpspeicherkraftwerken in der Schweiz im Rahmen der Energiestrategie 2050", Study commissioned by das Bundesamt für Energie (BFE), Frontier Economics, swissQuant Group, 2013.
- [Frost & Sullivan 2011] "Market Research Report - European UPS Market", Frost & Sullivan, December 2011. Available online: https://www.giiresearch.com/report/fs227341-european-ups-market.html
- [Genoese, Genoese 2014] Genoese, Fabio; Genoese, Massimo; "Assessing the value of storage in a future energy system with a high share of renewable electricity generation", Energy Systems, 2014.
- [Gifford 2015], Analysis: France's island solar+storage program presents EUR100 million opportunity, PV-magazine, June 2015. Available online: http://www.pv-magazine.com/news/details/beitrag/analysis--frances-island-solarstorage-program-presents-

eur100-million-opportunity_100019932/#axzz3eBhKgHky; Read more: http://www.pv-magazine.com/news/details/beitrag/analysis--frances-island-solarstorage-program-presents-eur100-million-opportunity_100019932/#ixzz4F3gC9gQf

- [GTAI 2015] „Market Status & Outlook on Batteries for Stationary Energy Storage in Germany“, GTAI, November 2015.
- [GTM 2016] "How Distributed Battery Storage Will Surpass Grid-Scale Storage in the US by 2020", GTM, Stephen Lacey, 10 March 2016. Available online: https://www.greentechmedia.com/articles/read/how-distributed-battery-storage-will-surpass-grid-scale-storage-in-the-us-b
- [Hopmann et al. 2014] Hoppmann J., Volland J., Schmidt T.S., Hoffmann V.H. (2014): "The Economic Viability of Battery Storage for Residential Solar Photovoltaic Systems - A Review and a Simulation Model", Renewable and Sustainable Energy Reviews 39, 1101–1118.
- [IAEW 2013] "Bewertung des Beitrags von Speichern und Pumpspeichern in der Schweiz, Österreich und Deutschland zur elektrischen Energieversorgung", IAEW, 2013.
- [IEA 2014a] "Technology roadmap – Energy storage", International Energy Agency, 2014. Available online:https://www.iea.org/publications/freepublications/publication/TechnologyRoadmapEnergystorage.pdf
- [IEA 2014b] "Energy Technology Perspectives", International Energy Agency, 2014.
- [IER 2010] "Herausforderungen eines Elektrizitätsversorgungssystems mit hohen Anteilen erneuerbarer Energien. Studie. Institut für Energiewirtschaft und Rationelle Energieanwendung", IER Universität Stuttgart, 2010.
- [IER et al. 2010] "Die Entwicklung der Energiemärkte bis 2030. Energieprognose 2009", IER Universität Stuttgart, RWI, ZEW, 2010.
- [INSIGHT_E 2014] "How can batteries support the EU electricity network?", KIC InnoEnergy, November 2014. Available online: http://www.insightenergy.org/static_pages/publications#?publication=5
- [IRENA 2015a] "Battery storage for renewables: market status and technology outlook", International Renewable Energy Agency, 2015. Available online: http://www.irena.org/DocumentDownloads/Publications/insight_Battery_Storage_report_2015.pdf
- [IRENA 2015b] "Renewables and electricity storage. A technology roadmap for Remap 2030", International Renewable Energy Agency, 2015. Available online: http://www.irena.org/DocumentDownloads/Publications/IRENA_REmap_Germany_report_2015.pdf
- [ISEA 2012] "Technology Overview on Electricity Storage. Overview on the potential and on the deployment perspectives of electricity storage technologies.", ISEA RWTH Aachen, June 2012.
- [ISEA 2016] "Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher. Jahresbericht 2016", ISEA RWTH Aachen, 2016. Available online: http://www.speichermonitoring.de/fileadmin/user_upload/Speichermonitoring_Jahresbericht_2016_Kairies_web.pdf
- [ISPE 2015] "Has time for batteries in Italy arrived or not?", Italian Institute for International Political Studies, 28 July 2015, available online: http://www.ispionline.it/en/energy-watch/has-time-batteries-italy-arrived-or-not-13748
- [IT-Times 2016] "Tesla Motors: Panasonic fürchtet Lieferengpässe bei Batterien", IT-Times, October 2016. Available online: http://www.it-times.de/news/tesla-motors-panasonic-furchtet-lieferengpasse-bei-batterien-120739/

- [Jentsch, et al. 2014] Jentsch, Mareike; Trost, Tobias; Sterner, Michael: Optimal Use of Power-to-Gas Energy Storage Systems in an 85% Renewable Energy Scenario. In: Energy Procedia 46, 2014, pp. 254–261. DOI: 10.1016/j.egypro.2014.01.180.
- [JRC 2011], "International Reference Life Cycle Data System (ILCD) Handbook—Recommendations for Life Cycle Impact Assessment in the European context", EUR 24571 EN, JRC, Luxemburg, 2011.
- [JRC 2014a] "Energy Technology Reference Indicator projections for 2010-2050", JRC, 2014. Available online: http://publications.jrc.ec.europa.eu/repository/handle/JRC92496
- [KEMA 2010] "Electricity Storage Association: Assessment of Jobs Benefits from Storage Legislation", KEMA Inc., March 2010. Available online: https://www.ice-energy.com/wp-content/uploads/2016/04/kema__esa_jobs_benefit_report_03_31_10.pdf
- [KFW 2016a], "Follow-up programme for promoting battery storage systems in connection with photovoltaic installations starts on 1 March 2016", KFW, 1 March 2016. Available online: https://www.kfw.de/KfW-Group/Newsroom/Aktuelles/Pressemitteilungen/Pressemitteilungen-Details_341696.html
- [KFW 2016b], "Erneuerbare Energien – Speicher", KFW. Available online: https://www.kfw.de/inlandsfoerderung/Privatpersonen/Neubau/F%c3%b6rderprodukte/Erneuerbare-Energien-%e2%80%93-Speicher-(275)/
- [KPMG 2016], "Development of decentralised energy and storage systems in the UK", KPMG. Available online: http://www.r-e-a.net/upload/rea_storage_report-web_accessible.pdf
- [Lazard 2015] "Lazard's levelized cost of storage analysis", Lazard, November 2015. Available online: https://www.lazard.com/perspective/levelized-cost-of-storage-analysis-10/
- [Low Carbon Futures 2012] "Pathways for energy storage in the UK", Centre for Low Carbon Futures, March 2012 . Available online: http://www.lowcarbonfutures.org/sites/default/files/Pathways%20for%20Energy%20Storage%20in%20the%20UK.pdf.
- [Lux Research 2016] "Recycling, not Reuse, Is the Better Choice for Batteries from Retired Electric Vehicles", Lux Research, 22 November 2016. Available online: http://www.luxresearchinc.com/news-and-events/press-releases/read/recycling-not-reuse-better-choice-batteries-retired-electric
- [MVV 2016] "Strombank – Innovatives Betreibermodell für Quartierspeicher", MVV, 10 October 2016.
- [National Grid 2015a], "Future Energy Scenarios", National grid, July 2015. Available online: http://fes.nationalgrid.com/fes-document/
- [National Grid 2015b], "System Operability Framework 2015", National grid, November 2015. Available online: http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=44046
- [National Grid 2015c], "Technical Guidance and Testing Procedure for Static and Dynamic Demand Response and Battery Storage Providers of Frequency Balancing Services", National grid, February 2015. Available online: http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=40571
- [National Grid 2015d], "Enhanced Frequency Response Webinar", National Grid, October 2015. Available online: http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=43334
- [National Grid 2016], "Enhanced Frequency Response - Frequently Asked Questions", National grid, March 2016. Available online: http://www2.nationalgrid.com/WorkArea/DownloadAsset.aspx?id=43939

- [NREAP IT 2010] "National Renewable Energy Action Plan in line with Directive 2009/28/EC", Italian Ministry for Economic Development, 30 June 2010. Available online: https://ec.europa.eu/energy/en/topics/renewable-energy/national-action-plans.
- [NPE 2016] "Roadmap integrierte Zell- und Batterieproduktion Deutschland", Nationale Plattform Elektromobilität (NPE), January 2016. Available online: http://nationale-plattform-elektromobilitaet.de/fileadmin/user_upload/Redaktion/NPE_AG2_Roadmap_Zellfertigung_final_bf.pdf
- [OFGEM 2015] "Low Carbon Networks Fund", OFGEM, 2015. Available online: https://www.ofgem.gov.uk/electricity/distribution-networks/network-innovation/low-carbon-networks-fund
- [Piergiorgio, et al. 2014] Piergiorgio Alotto, Massimo Guarnieri, Federico Moro, "Redox flow batteries for the storage of renewable energy: A review", Renewable and Sustainable Energy Reviews, Volume 29, January 2014, Pages 325-335, ISSN 1364-0321, http://dx.doi.org/10.1016/j.rser.2013.08.001. Available online: http://www.sciencedirect.com/science/article/pii/S1364032113005418
- [Planet GbR, et al. 2014] "Integration von Wind-Wasserstoff-Systemen in das Energiesystem", Planet GbR; Fraunhofer ISI; Fachhochschule Lübeck Projekt GmbH; KBB Underground Technologies; Institut für Energie- und Umweltforschung Heidelberg GmbH; 2014.
- [Pleßmann et al. 2014] Pleßmann, Guido; Erdmann, Matthias; Hlusiak, Markus; Breyer, Christian "Global Energy Storage Demand for a 100% Renewable Electricity Supply", Energy Procedia 46, 2014. DOI: 10.1016/j.egypro.2014.01.154.
- [Prognos 2011] "Bedarf an konventioneller Kraftwerkskapazität in Deutschland. Gutachten für die E.ON Kraftwerke GmbH", Prognos, 2011.
- [Prognos, et al 2011] "Energieszenarien 2011. Projekt Nr. 12/10", Prognos, EWI, GWS, 2011.
- [REA 2016] "Energy Storage in the UK - An Overview" Renewable Energy Association (REA), 2016. Available online: http://www.r-e-a.net/upload/rea_uk_energy_storage_report_november_2015_-_final.pdf
- [Regelleistung], Shared IT-platform for control power tenders installed by the German TSOs. Available online: https://www.regelleistung.net/ext/
- [RES LEGAL 2016], "Promotion. Feed-in tariff I (tariffa onnicomprensiva)", Renewable energy policy database and support, 2016. Available online: http://www.res-legal.eu/search-by-country/italy/tools-list/c/italy/s/res-e/t/promotion/sum/152/lpid/151/
- [RMI 2014] "The economics of grid defection", Rocky Mountain Institute, 2014. Available online: http://www.rmi.org/PDF_economics_of_grid_defection_full_report
- [RMI 2015] "The Economics of Battery Energy Storage. How multi-use, customer-sited batteries deliver the most services and value to customers and the grid", Rocky Mountain Institute, October 2015. Available online: http://www.rmi.org/electricity_battery_value
- [Roland Berger 2012] "Technology & Market Drivers for Stationary and Automotive Battery Systems", Roland Berger, presentation at Batteries, 15 November 2012. Available online: http://www.google.be/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=0ahUKEwjgwtiUoKnMAhWjOsAKHdzeAEoQFggoMAE&url=http%3A%2F%2Fonlinelibrary.wiley.com%2Fdoi%2F10.1002%2Fese3.47%2Ffull&usg=AFQjCNHD3n6z4jToxWqg-6RUg26G8Y3xfQ&sig2=EEc2-Zmg_hfA83FrSSKGHA
- [RVO 2016] "Stimulation of Sustainable Energy Production (SDE+)", RVO, 2016. Avaialble online: http://english.rvo.nl/subsidies-programmes/sde
- [RWTH 2016], "Wissenschaftliches Mess- und Evaluierungsprogramm Solarstromspeicher. Jahresbericht 2016", Institut für Stromrichtertechnik und Elektrische Antriebe der RWTH Aachen, 2016. Available online:

http://www.speichermonitoring.de/fileadmin/user_upload/Speichermonitoring_Jahresbericht_2016_Kairies_web.pdf

- [Sandia 2010] "Energy Storage for the Electricity Grid: Benefits and Market Potential Assessment Guide", Sandia National Laboratories, February 2010. Available online: http://www.ntis.gov/help/ordermethods.asp?loc=7-4-0#online
- [SCE 2016] "Amended Report of Southern California Edison Company (U 338-E) Demonstrating Compliance With Energy Storage System Procurement Targets And Policies", 26 March 2015.
- [Schabram et al 2013] Schabram, J.; Wiernes, P. E.; Linnemann, C.; Kraemer, C.; Moser, A.; Mercado, P. E. (2013): "Planning the future European power system". In: 2013 IEEE Grenoble PowerTech. Grenoble, France.
- [SEM 2014] "DS3 System Services Procurement Design and Emerging Thinking", Decision paper SEM-14-108, 19 December 2014. Available online: https://www.semcommittee.com/publication/sem-14-108-ds3-system-services-decision-paper
- [SRU 2011] "Wege zur 100 % erneuerbaren Stromversorgung", SRU, 2011.
- [Stedin 2015] „Annual report 2015", Stedin. Available online: http://jaarbericht2015.stedin.net/energietransitie/innovatie-en-samenwerking/nul-op-de-meter
- [Stenzel et al 2016] P. Stenzel, J. C. Koj, A. Schreiber, W. Hennings, P. Zapp, "Primary control provided by large-scale battery energy storage systems or fossil power plants in Germany and related environmental impacts", Journal of Energy Storage, Available online 15 January 2016, ISSN 2352-152X, http://dx.doi.org/10.1016/j.est.2015.12.006.
- [Stroomversnelling] Website on the Stroomversnelling inititative. Available online: http://stroomversnelling.nl/
- [Sukhvinder, et al. 2014] Sukhvinder P.S. Badwal, Giddey Sarbjit S, Munnings Christopher, Bhatt Anand Indravadan, Hollenkamp Tony"Emerging electrochemical energy conversion and storage technologies", Frontiers in Chemistry, volume 2, 2014, number 00079. Available online: http://www.frontiersin.org/Journal/Abstract.aspx?s=1469&name=chemical_engineering&ART_DOI=10.3389/fchem.2014.00079
- [Sullivan et al 2012] J.L. Sullivan, L. Gaines, "Status of life cycle inventories for batteries, Energy Conversion and Management", Volume 58, June 2012, Pages 134-148, ISSN 0196-8904. Available online: http://dx.doi.org/10.1016/j.enconman.2012.01.001.
- [TAB 2012] "Regenerative Energieträger zur Sicherung der Grundlast in der Stromversorgung", Büro für Technikfolgen-Abschätzung beim deutschen Bundestag Karlsruher Institut für Technologie (KIT), 2012.
- [Tennet 2012] „Rapport Monitoring Leveringszekerheid 2011-2027", Tennet, 2012. Available online: http://www.tennet.eu/nl/fileadmin/downloads/About_Tennet/Publications/Monitoring/plugin-2012-155_Rapport_Monitoring_2011-2027_Final20120630_Clean_tcm41-20796.pdf
- [Terna 2016] " Experiences and Initial results from Terna's Energy Storage Projects", Presentation Grid plus storage workshop, Terna, 29 February 2016. Available online: http://www.gridplusstorage.eu/workshops/6-workshop-7-croatia-italy-malta-slovenia-switzerland
- [Tilos 2014], "Technology Innovation for the Local Scale, Optimum Integration of Battery Energy Storage", 2014. Available online: http://www.tiloshorizon.eu/deliverables-publications/
- [TUDelft et al 2015] „Routekaart Energieopslag 2030", TUDelft, Berenschot, DNV, March 2015. Available online: http://topsectorenergie.nl/wp-content/uploads/2015/04/Systeemintegratie-Eindrapport-Perceel-2-Energieopslag-DNVGL-3-april-2015.pdf
- [UBA 2010] "Energieziel 2050. 100 % Strom aus erneuerbaren Quellen", UBA, 2010.

- [UK GOV 2013] "Energy storage: Eight great technologies", UK Government - Department for Business, Innovation & Skills, October 2013. Available online: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/249262/energy_storage_infographic.pdf

- [UK GOV 2013] "Energy storage: Eight great technologies", UK Government - Department for Business, Innovation & Skills, October 2013. Available online: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/249262/energy_storage_infographic.pdf

- [UK GOV 2014] "Electricity Market Reform: Capacity Market", UK Government, July 2014 (update February 2016). Available online: https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/249262/energy_storage_infographic.pdf
- [VDE 2012] "Energiespeicher für die Energiewende. Speicherungsbedarf und Auswirkungen auf das Übertragungsnetz für Szenarien bis 2050", VDE, 2012.
- [VDMA 2015] "Batterieproduktion in Deutschland – Chancen für den Maschinen- und Anlagenbau", VDMA Batterieproduktion, PEM der RWTH Aachen, 2015. Available online: https://battprod.vdma.org/documents/7411591/10499751/VDMA-RWTH_Batteriezellproduktion%20in%20Deutschland_web/3ff9ce4a-d821-41bb-ac53-3464b4687dbf
- [VITO 2016a], "Preparatory study on Smart Appliances – Task 6 - Draft", VITO, 20 May 2016. Available online: http://www.eco-smartappliances.eu/Pages/welcome.aspx
- [VITO 2016b], "Preparatory study on Smart Appliances – Task 7 - Draft", VITO, in review.
- [Younicos 2016], "Adiós Diesel, ahoy energy autonomy!", Younicos. Available online: http://www.younicos.com/en/projects/02_graciosa/
- [Zakeri et al 2015] Behnam Zakeri, Sanna Syri, "Electrical energy storage systems: A comparative life cycle cost analysis", Renewable and Sustainable Energy Reviews, Volume 42, February 2015, Pages 569-596, ISSN 1364-0321. Available online: http://dx.doi.org/10.1016/j.rser.2014.10.011
- [ZSW 2014] "Dynamische Simulation der Ausbauszenarien für erneuerbare Stromversorgung in Baden-Württemberg bis 2050 nach dem Gutachten zur Vorbereitung eines Klimaschutzgesetzes (SimBW). Speicherbedarf in Deutschland und Baden-Württemberg Abschlussbericht", ZSW, 2014

Appendix A: Summary of elements of 2030 visions

The scenarios of the ten year network development plan (TYNDP) 2016 look at how demand and generation could evolve in the future and how this would impact the pan-European electricity system. The report covers 5 scenarios: 4 with a 2030 time horizon and one looking at 2020. The table below shows the main assumptions and the characteristics of the energy system within the two selected 2030 scenarios i.e. the 2030 vision of "National Green Transition" and the 2030 vision of "European Green Revolution". [ENTSO-E 2015a]

Table 13: Summary of characteristic elements of four 2030 scenarios in the framework of the ten year network development plan [ENTSO-E 2015a]

	National green transition	**European green revolution**
Economic and financial conditions	More favourable	Most favourable
Focus of energy policies	National	European
Focus of R&D	National	European
CO_2 and primary fuel prices	high CO_2 price, low fuel price	high CO_2 price, low fuel price
RES	High national RES	On track to 2050
Electricity demand	Stagnation compared to 2020	Increase (growth demand)
Demand response (and smart grids)	Partially used	Fully used
	5%	20%
Electric vehicles	Electric plug-in vehicles (flexible charging)	Electric plug-in vehicles (flexible charging and generating)
	5%	10%
Heat pumps	Intermediate level	Maximum level
	5%	9%
Adequacy	National - autonomous high back-up capacity	European - less back-up capacity than V3
Merit order	Gas before coal	Gas before coal
Storage	Decentralized	Centralized

Appendix B: Applications DoE – BATSTORM

Table 14: Link between application as defined in the DoE database (rows) and the applications identified in this report (Columns)

	Self-Consumption	Energy Cost Management	Backup Power	Voltage Support	Frequency reserves	Black start capability	Island operation capability	Grid Congestion Relief	Grid Upgrade Deferral	Substation On-Site Power	Energy revenues Optimization	VRES integration
Black Start						√						
Electric Supply Reserve Capacity - Non-Spinning					√							
Electric Supply Reserve Capacity - Spinning					√							
Load Following (Tertiary Balancing)					√							
Ramping					√							
Voltage Support				√								
Electric Energy Time Shift		√										
Electric Supply Capacity												√
Transmission Congestion Relief								√				
Transmission Support								√				
Renewables Capacity Firming												√
Distribution upgrade due to solar									√			
Distribution upgrade due to wind									√			
Transmission upgrades due to solar									√			
Transmission upgrades due to wind									√			
Electric Bill Management		√										
Grid-Connected Commercial (Reliability/Quality)			√									
Grid-Connected Residential (Reliability)			√									
Frequency Regulation					√							
Transportable T&D Upgrade Deferral									√			
Stationary T&D Upgrade Deferral									√			
Onsite Renewable Generation Shifting	√											
Electric Bill Management with Renewables	√											
Renewables Energy Time Shift											√	
On-Site Power										√		
Transportation Services	√											
Microgrid Capability							√					
Resiliency			√									

Demand Response		√										

Appendix C: Energy Storage Ownership Models

Customer Ownership: The asset is bought outright by the customer, who then benefits from lowest cost of ownership, but is responsible for its maintenance and pays for equipment failures. The ownership model works best for technology enthusiasts and early adopters, who intend to utilize the full potential of their PV system and maximize self-consumption.

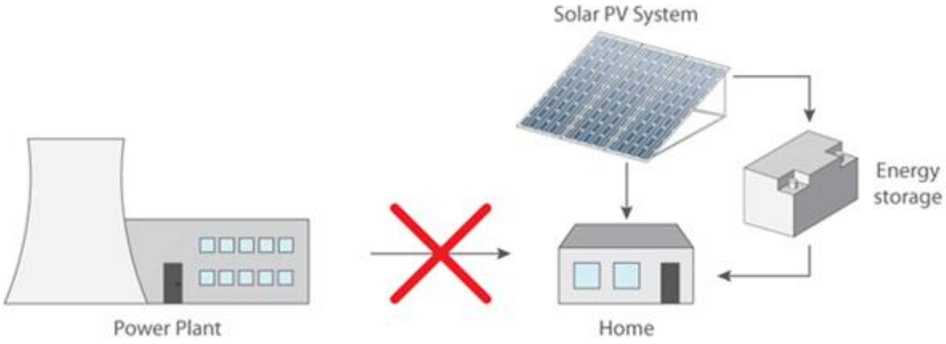


Figure 66: Customer Ownership[42]

Third party Ownership: The asset is owned by the energy solution provider, who bears a high upfront cost and ownership risk, while the customer pays for the service provided. This model transfers the risk of maintenance and equipment failure to the energy solution provider, however this gives them a greater control over the energy dispatch from the system. The energy solution provider optimizes the dispatch through a combination of PV, wholesale electricity and energy storage to meet the power purchase agreement.

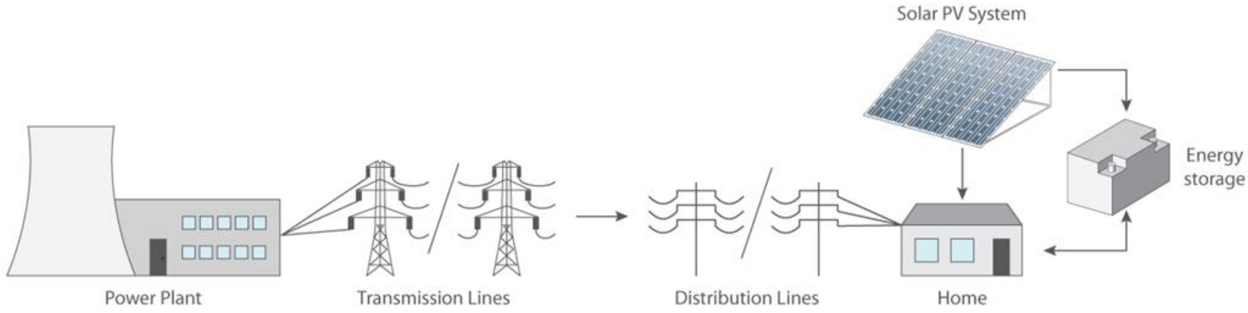


Figure 67: Third Party Ownership

---

[42] Images sourced from: http://reneweconomy.com.au/2014/three-possible-business-models-for-distributed-storage-62601

System Operator Ownership: The asset is owned by the system operator, while the storage capacity of the system is shared between the system operator and the customer. Although the asset's ownership is retained by the system operator, its use can be leased out to customers. The part of the energy from the system is stored and dispatched by the system operator to reduce the demand and strain on their network, while for the remaining part the customer decides its utilization.

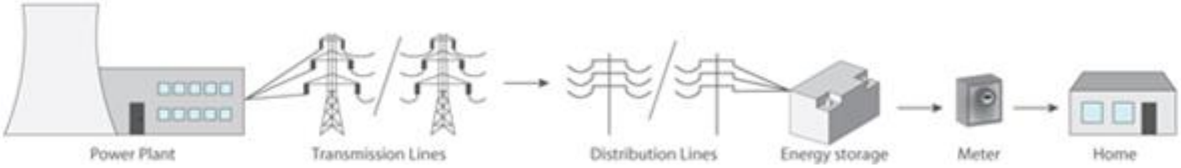


Figure 68: System Operator Ownership

Appendix D: Applications FfE – BATSTORM

Table 15: Link between application as defined in FfE (rows) and the applications identified in this report (Columns). [FfE 2016]

BATSTORM applications **FfE 2016 applications**	Self-Consumption	Energy Cost Management	Backup Power	Voltage Support	Frequency Containment Reserves	Frequency Restoration Reserves	Replacement Reserves	Black start capability	Island operation capability	Grid Congestion Relief	Grid Upgrade Deferral	Substation On-Site Power	Energy revenues Optimization	VRES integration
Self-consumption	√													
Energy cost management		√												
Primary reserve control					√	√								
Secondary reserve control						√								
Tertiary reserve control						√	√							
Congestion management / Redispatch										√				
Forecast deviation													√	√
Integration of RES surplus													√	√
Curtailment (Power production / Input management)													√	√
Increasing profitability of RES generation													√	

ECOFYS Germany GmbH

Albrechtstraße 10 c
10117 Berlin

T: +49 (0) 30 29773579-0
F: +49 (0) 30 29773579-99

E: info@ecofys.com
I: www.ecofys.com

ECOFYS Germany GmbH

Albrechtstraße 10 c
10117 Berlin

T: +49 (0) 30 29773579-0
F: +49 (0) 30 29773579-99

E: info@ecofys.com
I: www.ecofys.com