Battery Storage: Still Too Early?

A report by Arthur D. Little

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Content

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Executive summary

Renewable energy deployment over the last decades has posed unprecedented challenges for the planning and operation of power systems. In the context of increasingly decentralized and intermittent generation, power utilities[1] and system operators need to rethink their portfolios, business models and positions in the market in order to be resilient to these changes and benefit from them.

Battery storage has gained strong interest as an option to respond to these new challenges and provide flexibility to the system to cope with high levels of renewables. Driven by increased usage in the automotive industry, costs of batteries have significantly dropped since 2010 (65% decrease for lithium-ion batteries[2]), although further cost reductions are necessary for widespread use in the power sector.

Actors all along the energy value chain find themselves facing a number of key questions when considering how energy storage may affect their businesses:

- In what applications will battery storage play a key role in managing the future grid?
- What will be the most attractive business models? For which (combination of) actor(s) along the value chain?
- What factors influence the choice of battery technologies?
- Which battery technologies will likely be the most important in each application?
- What are the drivers, enablers and alternatives to battery storage deployment?

In this report we respond to the above questions and describe the results of a study in which we have reviewed battery applications, battery types, drivers & barriers to battery storage and trends in key markets, based on interviews with major market players in the energy sector. We have explicitly addressed what's in it for the different types of stakeholders along the value chain. The key conclusions of our study are summarized below:

Deployment of stand-alone batteries to provide grid services such as frequency response and frequency regulation has mainly been achieved under pilot projects. Widespread deployment has been hindered by high costs and regulation uncertainty, but grid-scale storage for **frequency regulation**[3] is still seen as one of the most promising applications to date. Large-scale hybrid battery configurations, to **stabilise renewables output**, are also considered one of the biggest successes of batteries so far, especially on islands. Finally, **hybrid residential battery** configurations have seen a significant boost in some markets, such as Germany, where incentives are put in place.

1 For the purpose of this study the term "power utilities" includes generators (i.e. IPPs) and vertically integrated utilities (involved in generation, trading and retail), and excludes system operators, which are considered separate categories.
2 Bloomberg New Energy Finance, 2016.
3 Equivalent of FCR in ENTSOE terminology

DSOs and TSOs can use batteries for grid-support applications such as congestion avoidance, frequency regulation, frequency response[4] and voltage stability, and tend to see co-ownership as the most likely option for making a positive business case. Indeed, all market players generally see the **combination of several applications** as essential to make battery solutions economically viable. However, system operators are only likely to make major moves when the regulatory framework for ownership and operation of storage technologies has been further clarified.

Compared to system operators, power utilities are able to leverage batteries for a wider range of applications and less constrained by regulation. They can potentially use batteries to generate revenues from arbitrage in the market, decrease exposure to imbalance costs and provide grid services to system operators. Vertically Integrated Utilities (VIUs)[5] can also deploy batteries as part of their offerings to end customers, as is already seen in Germany, for example.

Aggregators are also major enablers of battery deployment today. Partnerships between VIUs and aggregators as well as battery manufacturers/system integrators and aggregators have been developed over the last few years to generate revenues primarily from ancillary services and the wholesale market with batteries at residential, commercial and industrial levels. The roles of aggregators continue to evolve, and the emergence of aggregators acting as software providers rather than technology operators is reshaping the position of VIUs in the market.

In conclusion while battery storage remains a market for early adopters today, with more mature business models for some players (e.g. power utilities) than others (e.g. system operators), time for inaction is far over.

Because whenever the technology shall be cheap, it will belong to those who invested in its development. And whenever the regulation will be more facilitating, the opportunities will be captured by those who have a business model ready.

This is the moment for markets to be shaped, lobbying to be done, regulators to engage with and early strategic actions to be performed for actors along the energy value chain to make sure they will be part of the future framework and at the forefront of market trends.

Contributions

Our additional thanks for contributions from Eirgrid and other network operators as well as from multiple storage technology providers

4 Equivalent of FRR in ENTSOE terminology

5 Power utilities involved in several steps of the supply chain, including generation, trading and retail (e.g. Engie, E.ON).

1. Batteries to support the energy transition

The power grid is in the midst of unprecedented change. Large amounts of renewables are being added to the grid in many parts of the world, coal and nuclear generation are increasingly disfavored, and there is a shift from the old centralized model of generation, transmission, and distribution to a more dynamic grid incorporating diversity of generation assets on a range of scales.

While generally positive from an environmental perspective, such changes present a number of challenges to grid operation, particularly for managing the integration of intermittent renewable generation technologies such as solar PV and wind. Among multiple solutions[6], energy storage will likely play a critical role in managing such challenges, for example, by smoothing the output from renewable sources and storing energy in times of high generation for later release when demand is strong.

Due to their flexibility, applicability on wide scale, and potential synergies with other applications such as electric vehicles, **electrochemical storage technologies** have received particular attention in recent years.

While battery storage remains marginal (less than 1 GW) today[7], the announcements of several large-scale commercial projects and some major transactions over the last year are clear signs that the sector is taking off.

Several models have emerged in which existing and new players in the power sector deploy and operate batteries to respond to the new challenges. Progress on both the technology and regulation fronts are necessary to clear uncertainties as to whether batteries are economically sound, and for whom.

This paper analyzes how battery storage can respond to the energy transition and addresses:

1. The applications of batteries and business models across the value chain;
2. Subcategories of electrochemical batteries, their characteristics, costs and specific fields of application;
3. The drivers for battery deployment and diagnostics in key country archetypes.

Recent major transactions and alliances in the battery storage sector

6 Interconnection, Demand Side Management, flexible generation
7 Bloomberg New Energy Finance

2. A business for all, except for system operators?

Batteries can be used at different **levels of the electricity system** and in **various applications**, from providing grid-support services to generating revenues from price spread in wholesale markets.

The main types of applications are briefly detailed below:

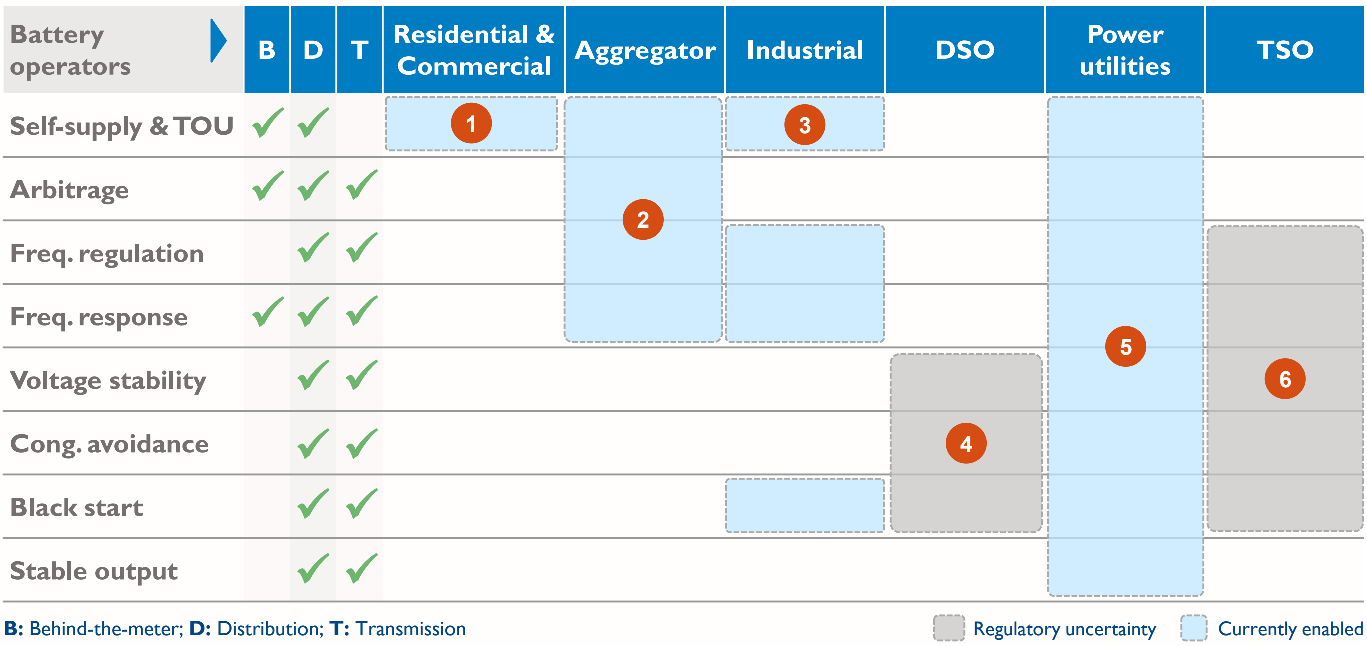
Terms[8]	Description
Self-supply & TOU	▪ Combined physically (hybrid systems) or virtually with distributed renewable sources, distributed storage behind the meter or on the distribution network allows at least partial self-sufficiency, resulting in decreased costs for grid supply and reduced exposure to price fluctuations. Savings could also be achieved by optimizing consumption based on time of use (TOU) and related price profiles ▪ Stand-alone, they improve reliability and power quality to end users in markets with poor security of supply or access to power supply
Arbitrage	▪ Batteries potentially located at any level on the grid (distribution, transmission or behind the meter aggregated as a virtual asset) are used to exploit the wholesale electricity price spread and charge during off-peak periods while discharging in peak periods (peak shaving) *Note that Time Of Use (TOU) included in the above application is also a form of arbitrage but operated by end-users (residentials, industrials).*
Frequency regulation[9]	▪ Under normal operating conditions, continuous charge and discharge of batteries located at distribution or transmission can maintain demand and supply in balance and keep frequency within required limits
Frequency response[10]	▪ Under contingency conditions, when system failure leads to major and sudden frequency variation, batteries are activated to restore primary control ▪ Batteries at distribution, transmission or behind the meter are aggregated as virtual assets
Voltage stability	▪ Batteries, at specific locations in the distribution and transmission network, release or absorb reactive power to maintain power quality locally
Congestion avoidance	▪ Charge and discharge of batteries, at specific locations in the distribution and transmission network, enable postponing investments, remaining compliant during works on the network, and increasing renewable penetration where the limits of the grid are reached in order to avoid congestion at substations during local peak periods
Black start	▪ Batteries, at specific locations in the distribution and transmission network, are used to energize pieces of the network when there is a black-out
Stable output	▪ Batteries at distribution or transmission level, combined with intermittent renewables (e.g. wind, solar) enable the generator to smooth output to comply with regulatory duties or mitigate imbalance

The majority of the above applications can be stacked, allowing the operator/owner of the battery to capture the value across several services. For example, a wind-farm operator would install a battery to stabilize its output and limit imbalance costs while also capturing revenues through the provision of ancillary services[11].

Figure 1 maps stakeholders across the value chain to the potential applications they will address when operating batteries.

8 Ancillary services/operating reserves required by TSOs/DNOs have been classified into frequency regulation, frequency response, voltage stability and black start. Planned/ strategic reserves (e.g. capacity mechanism) are considered as a way for batteries when operated under a specific application to capture additional revenues.
9 Equivalent of FCR in ENTSOE terminology
10 Equivalent of FFR in ENTSOE terminology
11 Services identified as necessary by the transmission or distribution system operator to enable them to maintain the integrity, stability and power quality of the transmission or distribution grid

Figure 1: Mapping of battery operators & key applications



1 Equivalent of FCR in ENTSOE terminology
2 Equivalent of FRR in ENTSOE terminology

Power utilities, and in particular vertically integrated utilities (VIUs)[12], are the only players in a position to address all major applications, from providing support to the grid to maximizing revenues from the wholesale market and operating batteries to optimize consumption. However, their ability to stack these applications strongly depends on the accessibility and definition of these services and the extent to which they are mutually exclusive.

The same application often sees several competing models across the value chain (R&D, development, ownership, operation and maintenance) able to provide the services and possible structures or business models are discussed below:

Residential & commercial

Three main reasons can lead the residential & commercial sector to operate batteries:

- **Poor security of supply**, with frequent outages: battery is an emergency back-up if an outage occurs. However, the business case remains challenging and depends on the value of stable supply and loss load, which is especially hard to assess at residential level.
- **Poor access to the main grid** and the possibility, with battery storage combined with distributed generation, of remaining off-grid. Battery storage is, for example, installed in telecom towers and responds to the needs of telecommunication networks willing to expand to the remotest places in the world and provide uninterrupted supply. The telecom sector is the leading market for commercial use of battery storage so far and, as such, the market is expected to grow at 10% over the next five years[13] in key markets such as India and Africa.
- Desire to become more **self-sufficient and reduce electricity costs** by combining storage and distributed generation (e.g. PV panels) and increase self-production.

OEMs and system integrators[14] such as Tesla sell directly to end users or through the intermediary of official suppliers[15], which install the technology at the end user's premises. End users, in turn, operate and own or potentially lease[16] the devices. A leasing business model for residential batteries can be particularly interesting in facilitating the combination of storage applications that span multiple stakeholders. In Germany, for example, residential hybrid PV/battery systems are mainly used to increase self-consumption during summer months, and the batteries' state of charge is near zero during the first three months of the year. This means system operators could potentially use residential batteries for grid-support applications during this period. Such a business model could be

12 Power utilities involved in several steps of the supply chain, including generation, trading and retail (e.g. Engie, EON)
13 *Economic Times*, March 2016
14 System integrators are responsible for packaging the batteries and adding auxiliaries such as control systems
15 VIUs or distributors of battery solutions
16 The leasing model is quite common for solar PV and CHP

facilitated through a leasing contract, and enables residential and commercial customers to benefit from the use of batteries for other applications and improve the business case.

Other business models have been developed to leverage batteries owned by residential and commercial customers to capture price spread and/or ancillary revenues via aggregators and VIUs. These models are discussed below.

Aggregators

The aggregator role has developed to fill the gap left by increasingly distributed generation that is unable to participate in the energy and ancillary services market. Aggregators effectively aggregate a large number of generation and demand sources into controllable power plants referred to as virtual power plants (VPPs).

The German, French, Belgian and UK markets have been incubating virtual power plants for five years now. VPPs have started to become viable, but this evolution will accelerate by decreasing battery cost and involvement of strong players in the market such as Tesla. In Germany, Tesla and Sonnenbatterie signed deals with VPP player Lichtblick to link residential batteries to the control platform last year. Savings can be passed on to customers in multiple ways (not comprehensive): through direct payment to the end customers when the aggregator is using the scheme or fixed yearly payment (preferred models so far); under a profit-sharing model; or upfront as a discount on the battery investment costs (with the challenges that it poses in terms of forecasting reserve-auction results).

The provision of ancillary services by aggregators is a proven model tested through demand-side response for years now. Electricity trading by aggregators for arbitrage, on the other hand, faces more hurdles because of the volume of imbalances it can cause for balance-responsible parties (BRPs)[17] prior to the settlement process.

Therefore, coordination between aggregators and BRPs is needed for aggregators to operate in a deregulated energy market (e.g. day-ahead or intraday). Aggregators have been working hand in hand with VIUs, which enable aggregators to not only overcome the balancing-responsibility issue mentioned above, but also channel their business propositions to end customers. However, as the market matures, we can observe a progressive split between aggregators willing to remain operators of flexibility in the system and those focusing more on selling the demand-response management software (e.g. AutoGrid Flex from Autogrid). This evolution might, in turn, fuel a shift for VIUs, which will reposition themselves in the market and offer these services without aggregators.

More specific to the commercial and industrial sectors, energy service providers (e.g. Dalkia, part of VIU EDF) have also acknowledged the potential of acting as aggregators. We can expect them to play an important role in leveraging additional value from battery storage building on their current client bases and further transform the aggregator landscape in the near future.

Industrials

Similar to the residential and commercial sector, industrials are likely to use batteries to cope with power-outage issues and become more self-sufficient, as well as avoid network charges where consumption is measured at certain times of the year. Industrials will either operate their battery storage themselves in the same way they participate in ancillary services or outsource the operation to power utilities or aggregators.

Depending on their size and the part of the network they are connected to, industrials could be partnering with DSOs and TSOs in order to optimize their consumption patterns while generating revenues from grid-support activities (e.g. voltage stability, black start). We see few applications of this business model to date, but it can be a particularly good alternative for system operators that have their hands tied regarding their roles in storage activities.

DSO

The integration of renewables poses a number of challenges for DSOs in terms of power quality and grid reinforcement to accommodate renewables at their maximum potential.

Batteries deployed in strategic locations of the network have the potential to relieve grid congestion and therefore avoid or postpone grid reinforcement. Battery storage, in this case, finds itself playing a role in the medium- and long-term operation and planning of the system. However, batteries today remain, in most markets, too expensive and do not present favorable economics relative to the critical time of use and/or alternative system-wide upgrades.

Another field of application for batteries is the provision of voltage control to improve the quality of supply, but this is likely to be only as part of a wider set of applications, given that it can be achieved through other, cheaper components of the network (e.g. stand-alone inverters).

In Europe, the unbundling of the sector has confined system operators (DSOs, TSOs) to owning and operating transmission and distribution assets only. It has not been clear so far whether some regulatory bodies consider battery storage a generation

17 Entities responsible for composing a balanced portfolio of generation and consumption

asset, but the European Commission (EC) recently proposed a definition for energy storage and the principles of its deployment (see box page 11.) This will hopefully mark the beginning of the end of a period of uncertainty regarding the exact roles that system operators can take with batteries. In the meantime, system operators are already considering innovative business models to deploy batteries without entering the energy market.

Examples of such business models are the deployment of batteries at complementary locations in the network (centralized and congested areas) in order to neutralize the charging and discharging effects and avoid interacting with wholesale markets to balance the network (Tennet, the Netherlands).

Regulatory uncertainty so far and challenging business cases explain why the track record of commercial battery deployment for distribution-grid applications remains poor today. While many pilots have been running in Europe and worldwide to test the technology and its performance for specific applications, actual commissioning of battery solutions for commercial grid applications is limited.

EDP (Portugal) is testing concrete applications of distributed energy storage and energy management in the distribution grid to demonstrate the relevance of storage for power-supply reliability and power quality in partnership with Siemens and the University of Evora. The project was commissioned in December 2015 and focuses on storage for rural/semi-urban grids as part of a wider program led by Siemens.

Potential business models will develop as regulation and costs evolve, but the general view among DSOs (EDP, Eandis) is that shared operation of batteries will be necessary for DSOs to build viable business cases while sticking to their areas of activities.

"Storage could become an asset in the grid to overcome local (extreme) congestion, and to protect the power quality and security of supply but only when techno-economically a better solution than the current alternatives. In that case and for that part DSO could be the owner of the storage but it is more likely that they would lease or use or (in what way possible) a part of a battery that was installed by a third party on the grid" (Eandis, Belgian DSO).

Power utilities[18]

Vertically Integrated Utilities (VIUs), being at the interface between end customers and system operators, have the potential to play a significant role in the battery market.

In their capacity as retailers, they act as enablers for deployment of residential battery storage. In adding battery storage as part of their energy services packages, VIUs aim at differentiating themselves and benefiting from extra revenue streams. Several VIUs in Germany are offering battery solutions to their customers. E.ON, for instance, released its home storage system combining PV, storage, app and tariff in April 2016.

In Benelux Eneco has been supplying the Tesla Powerwall to its customers since the start of 2016. A couple of months later it expanded its services to CrowdNett with the support of Tesla, SolarEdge and Ampard. The software developed by Ampard allows controlling residential batteries remotely so they can participate in the provision of ancillary services. In exchange for the use of 30% of the battery capacity, residential customers receive 450€ in compensation guaranteed over the next five years.

Beyond the retail side, battery storage represents a key opportunity for VIUs and generators to:

- Decrease exposure to imbalance charge from renewables intermittency
- Optimize asset production and sales in the wholesale market based on market signals (arbitrage)
- Capture revenues from ancillary services and capacity mechanisms
- Support industrial or consumer groups in avoiding system charges, where these are calculated based on consumption at peak periods, and negotiate to receive a portion of this saving

Among the above applications, the latter two are good entry points for new entrants, aggregators, energy traders and merchant players to generate revenues of battery storage under a more opportunistic approach than incumbents.

The possibility for power utilities to combine revenues from multiple applications improves the battery business case but depends on market design specifics (e.g. provision of multiple services to multiple parties at the same time).

An example of production optimization/arbitrage can already be seen on a large scale in the US, where we expect that within four years the world's biggest storage capacity project in Los Angeles will be delivering over 100MW for about four hours at peak period[19].

Finally, depending on local regulations, generators might have to comply with specific ramp-up and ramp-down profiles and

18 For the purpose of this study the term "power utilities" includes generators (i.e. IPPs) and vertically integrated utilities (involved in generation, trading and retail), and excludes system operators, which are considered separate categories

19 *Scientific American*, July 2016

therefore be obliged to couple intermittent generators with battery technologies on site. Islands are a good example of markets where such constraints have been put in place (e.g. Puerto Rico, La Réunion).

TSO

In the same way TSOs might contract with power utilities and large customers for ancillary services (frequency response, voltage control) and reserve (strategic reserve through capacity mechanisms), they could potentially meet their requirements by owning batteries.

However, similar to DSOs in Europe, the business models under which TSOs will be able to own and operate batteries remain to be defined in most countries. Market solutions are always preferred. The development and ownership of batteries by TSOs raise questions about market distortion and funding of regulated monopolies. But some players have highlighted the necessity, when market conditions are not appropriate and a solution is required, to implement storage through a regulated solution (Red Electrica and ENTSO-E[20], Terna).

In Italy the regulatory framework was adapted to allow for the TSO Terna to develop and operate batteries in the network. Two major pilots, respectively, of 40 MW in Sicily and Sardinia (power-intensive projects) and 35 MW in South Italy (energy-intensive projects) are being led by Terna in collaboration with universities and research companies to prove the applicability of batteries for system balancing, ancillary services, power quality and tertiary reserve. The technologies under consideration include lithium-ion, flow and sodium-sulphur batteries.

Again, transmission system operators such as National Grid and Tennet agree on the fact, to make the business case positive, multiple value streams and collaboration between different market players are required.

Because of their scalability and the multitude of applications they address, batteries can be owned and operated by many market players. Figure 2 shows the position of key market players across the value chain and potential business models.

Figure 2: Potential business models across the value chain

End Customers	R&D, manufacturing	Development & Integration	Ownership	Operation	Maintenance
1 Residentials & Commercials as battery operators	Battery OEM	System integrator/ battery distributor	R&C	R&C	System integrator/ battery distributors[1]
	Battery OEM	System integrator + Utility	Utility: leasing model	R&C + utility	Utilities[1]
	Battery OEM	System integrator + DSO	DSO: leasing model	R&C + DSO	System integrator[1]
2 Aggregators as battery operators	Battery OEM	System integrator	R&C	Aggregator	System integrator[1]
	Battery OEM	System integrator	Industrial	Aggregator	System integrator
3 Industrials as battery operators	Battery OEM	System integrator + utility	Industrial	Industrial + utility	System integrator
	Battery OEM	System integrator	Industrial	Industrial	System integrator
4 DSOs as battery operators	Battery OEM	System integrator + DSO	Industrial	Industrial + DSO	System integrator
	Battery OEM	System integrator + DSO	DSO	DSO	System integrator
5 utilities as battery operators	Battery OEM	System integrator + utility	Utility	Utility	System integrator
	Battery OEM	System integrator + utility	Utility	Utility	Utility
6 TSOs as battery operators	Battery OEM	System integrator + TSO	TSO	TSO	System integrator
	Battery OEM	System integrator + TSO	Industrial	Industrial + TSO	System integrator

Operator | Structure to be developped pending regulation

1 Few maintenance needed

20 Energy Storage, global conference – Brussels – 2016 regarding law adaptation for energy storage in Gran Canaria

The gap in the regulatory framework regarding batteries in markets such as Europe has slowed down development of clear strategies and business models by system operators, but positive signs have been seen recently (ENTSOE, Ofgem, the European Commission) to establish a clear framework and market mechanisms for batteries.

In an attempt to clarify the legislative framework in which batteries operate, the European Commission released the Electricity New Market Design Package in November 2016, providing clarifications on the role of system operators with respect to energy storage in their proposal for a revised electricity Directive. The EC states that *"Transmission system operators shall not be allowed to own, manage or operate energy storage facilities and shall not directly or indirectly control assets that provide ancillary services".*

However, under some conditions, TSOs could derogate from this obligation:

"(a) other parties, following an open and transparent tendering procedure, have not expressed their interest to own, control, manage or operate such facilities offering storage and/or non-frequency ancillary services to the transmission system operator;

(b) such facilities or non-frequency ancillary services are necessary for the transmission system operators to fulfil its obligations under this regulation for the efficient, reliable and secure operation of the transmission system and they are not used to sell electricity to the market; and

(c) the regulatory authority has assessed the necessity of such derogation taking into account the conditions under points (a) and (b) of this paragraph and has granted its approval."

In addition, the EC provides with a definition for energy storage as *"deferring an amount of the electricity that was generated to the moment of use, either as final energy or converted into another energy carrier".*

Despite those propositions, EASE (European Association for Storage of Energy) requests the EU to recognize energy storage as a separate asset class, alongside generation, transmission/distribution and consumption to avoid the unwarranted double charging (energy imported from the grid and exported to the grid, including levies and taxes) imposed to storage facilities, which does not reflect the value of storage to the grid.

"Power utilities, and in particular vertically integrated utilities, are the only players in a position to address all major applications, from providing support to the grid to maximizing revenues from the wholesale market and operating batteries to optimize consumption."

3. High synergies with other sectors will push Li-Ion batteries

For grid applications three critical parameters characterize the performance of electrochemical storage technologies and are the most important in the selection of a technology:

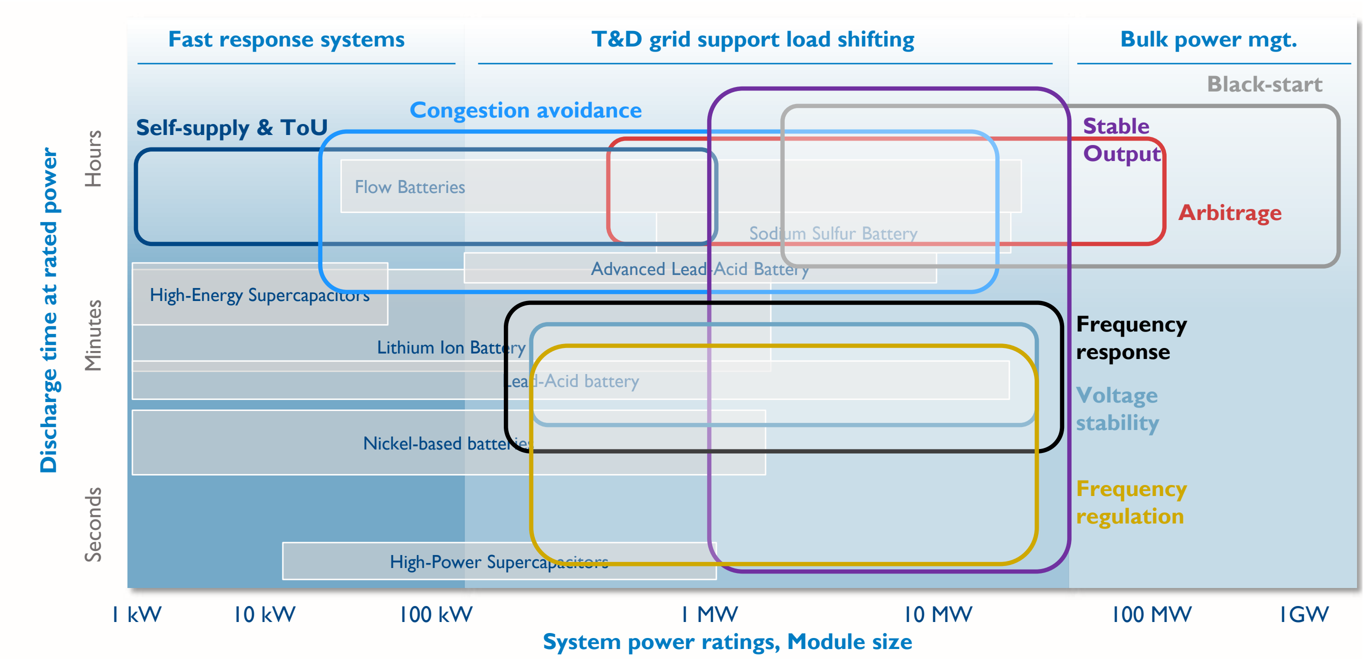
- **Response time** is how quickly a storage technology can be brought online and discharge energy
- **System power rating** is the maximum output available to address flexibility needs
- **Discharge duration at rated power** is how long a storage device can maintain output

Potential applications for a given technology will depend on the balance between these parameters. For example, technologies with high power capabilities and rapid response but short discharge times will lend themselves to applications such as frequency regulation, but will struggle with large-scale energy storage applications such as arbitrage. Conversely, technologies with very long discharge times but slow response times would be good for arbitrage or stabilizing output from renewables, but may not be suitable for applications such as frequency response, which require rapid changes in output. Figure 3 maps applications to power ratings and discharge times, and also indicates where some of the major technologies (see discussion below) are most applicable.

In addition to the main parameters, the following factors are important when considering an investment decision:

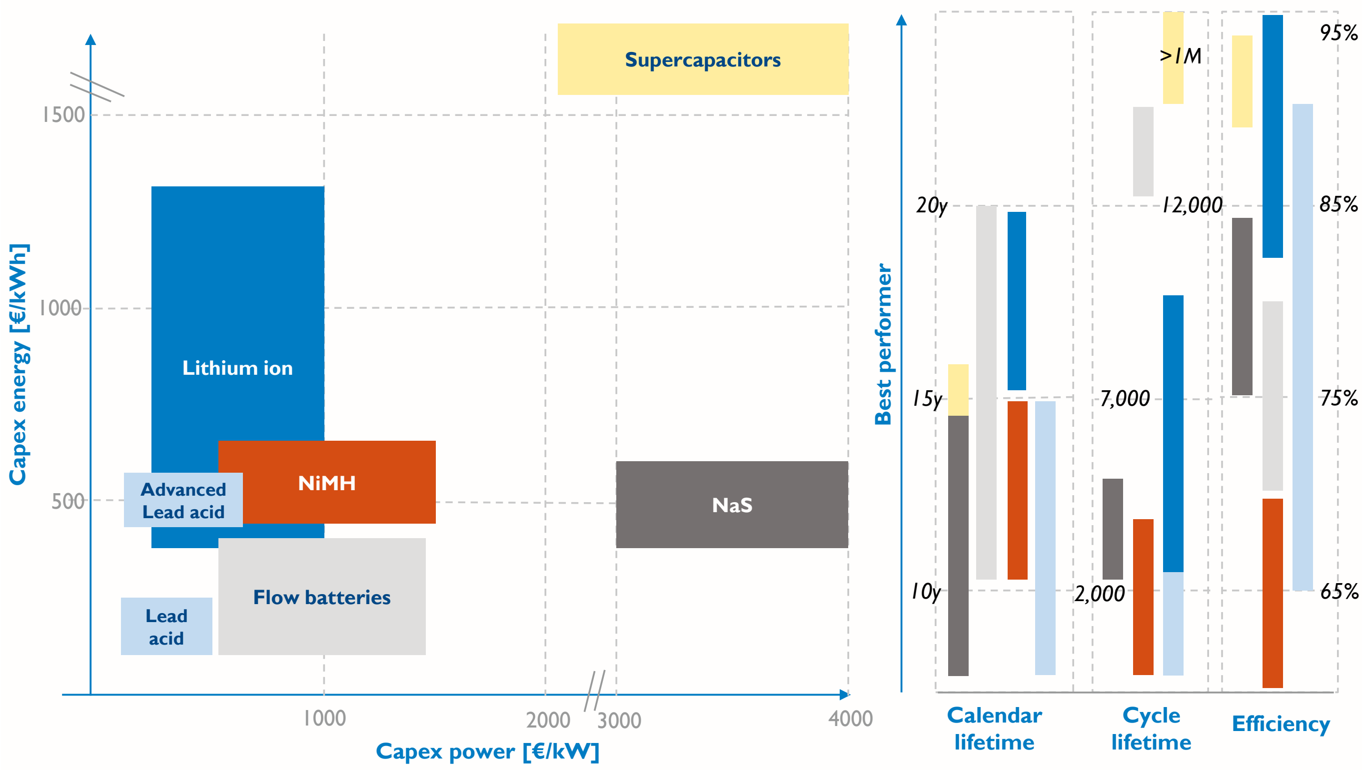
- **Reliability**, in terms of percentage of time that the capacity is available when needed. Utilities require >99% reliability
- **Energy and power density**, amount of power or energy stored per unit of volume and/or weight. Determines the practicality of a given application and technology combination
- **Calendar lifetime**, time before the battery capacity decays below usable levels (usually a function of temperature and time)
- **Cycle lifetime**, number of cycles (charge discharge) before the battery capacity drops below usable levels
- Efficiency, in terms of delivered power versus input power, >90% is desired, >75% is acceptable

Figure 3: Mapping of battery technologies and applications to key functionalities



Source: Purdue, Arthur D. Little analysis

Figure 4: Key drivers of levelized costs per battery type[21]



Finally, **cost**, often expressed as Levelized Cost of Storage (LCOS)[22], is a critical parameter which will determine the economic viability of a given application. The LCOS of electrochemical storage technologies is a function of the upfront capital costs, lifetime (calendar and cycle), efficiency and particular characteristics of the application. This is discussed in more detail below.

From a technology point of view electrochemical systems encompass an array of chemistries, ranging from familiar lead-acid and lithium-ion systems, to less well-developed approaches such as flow and sodium-sulphur batteries, through to emerging battery chemistries such as zinc-air, lithium-air, sodium-ion and lithium-sulphur. Supercapacitors, which store charge in an electrostatic field, also fall into this category. An overview of the key cost parameters for the main battery types is provided in Figure 4.

Due to strong synergies between power applications and both electric vehicles and consumer electronics, much of the recent focus of battery development has been on **lithium-ion (Li-ion) batteries**. Indeed, Li-ion systems do have a number of advantages for grid applications, including high energy density, rapid response, very high efficiencies and flexible operation (discharge from seconds to four or five hours). These features enable lithium-ion batteries to be used for most applications in principle.

Furthermore, massive investment by companies such as Tesla/Panasonic and LG Chem is pushing down costs (and raising production rapidly). For example, battery packs for vehicles from some of the major players (Nissan (Leaf), General Motors (Volt) and Tesla (Models S and X)) decreased by 70% from 2005 to 2015.[23] While lead acid batteries' retail prices have decreased by 5% in Germany over the last three years, retail prices of Li-ion batteries have fallen by close to 20% over the same period[24]. Additionally, the technology continues to evolve and improve, with many new chemistry variants under investigation. This will be further analyzed in our forthcoming study on *Battery Technologies and Costs*.

21 EASE, Resource-E-Storage report 2016, Hybrid energy storage systems for renewable energy applications, ENEA consulting, Energy Storage, global conference – Brussels – 2016
22 Total lifetime cost of battery divided by the cumulated stored energy. The LCOS can be used as a first indicator to compare costs between different battery types and broadly position batteries compared to more conventional generation. However, levelized costs highly depend on the applications and batteries and should only be compared on this basis. (See discussion in text)
23 Source: Nissan, Tesla Motors, DOE, Deutsche Bank, BNEF, Navigant, EIA, Arthur D. Little analysis
24 Energy Storage, global conference – Brussels – 2016

Nevertheless, Li-ion batteries do suffer from some disadvantages. They remain relatively expensive, in both energy and power terms, despite recent cost reductions.[25] Additionally, safety remains an issue as electrodes are thermally unstable, which can lead to a thermal runaway. This means complex electronic circuitry is needed to reduce the prospect of fires or explosions to an acceptable level, which adds further cost. The disadvantages reduce the prospects for Li-ion batteries to be used in bulk energy-storage applications requiring many hours of storage capacity, e.g. arbitrage.

Despite poor lifetime and average efficiency, **lead acid batteries** remain the technology with the best cost/performance ratio today in terms of capital cost per kWh and kW. There is room for further cost reduction through mass production. Disadvantages of lead acid batteries include low energy density, which can be challenging in some locations (e.g. Japan), and toxic chemicals content. The technology is mature, but new generations of advanced lead acid batteries with improved performance (e.g. lifetime, energy density) continue to be introduced. Lead acid batteries can be used in most applications except arbitrage, given their energy density and therefore limited discharge capabilities at rated output.

Sodium-Sulphur (NaS) batteries have high power, high energy density and high discharge time, and are therefore particularly suitable for intraday energy applications (arbitrage, self-supply & TOU, stable output). The technology is approaching the maturity phase. NaS batteries rank average in terms of investment costs, efficiency and lifetime, leading to levelized costs on average higher than lead acid batteries, with less cost reduction potential than lithium-ion and lead acid batteries.

Flow batteries are at the R&D stage. One of their main advantages is the decoupling of energy and power. The main drawbacks to date include poor efficiency, low energy density and the use of toxic chemicals. Maintenance and reliability are also significant concerns. Similar to NaS batteries, flow batteries are best suited for large-scale energy applications such as arbitrage and stable output applications.

Supercapacitors have very quick reaction time and very high cycle lifetime, making them particularly fit for frequency regulation applications. Supercapacitors have low energy density and their costs remain prohibitive today for energy applications.

Nickel-metal hydride (NiMH) batteries remain costly today, with generally poor performance regarding lifetime and efficiency. They are particularly suited for frequency-response, frequency regulation and voltage-stability applications. Safety under high-power charge or discharge is an advantage versus lithium-ion technologies, and strong resistance makes NiMH batteries the preferred technology for applications in the transportation sector and extreme conditions (e.g. remote, off-grid).

Today, **the cost of battery storage technology is too high for large-scale commercial deployment**, other than where local regulations incentivize its deployment (See Section 5). Calculating LCOS is complex since it depends on the application characteristics, the overall system configuration, and the average shape of the charge and discharge curves, in addition to the basic parameters of the battery system (capex, efficiency, lifetime, etc.).[26] Values of the incremental cost of battery storage observed in the literature range between 400 €/MWh and 2,000 €/MWh for lead acid, between 200 and 1,500 €/MWh for Li-ion, between 350 and 1,000 €/MWh for NaS, and between 250 and 1,500 €/MWh for flow batteries. These levelized cost ranges are wide, even within specific applications, and will be investigated in detail in our next publication focusing on *Battery Technologies and Costs*. Estimates of the levelized costs of other alternatives such as reciprocating engines (between 150 and 200 €/MWh for gas and between 200 and 300 €/MWh for diesel)[27] suggest that in some cases batteries could be competitive, but for most applications the business case is not attractive compared to other alternatives.

However, as noted above the cost of batteries continues to fall, particularly in Li-ion, in which leading players are making huge investments in a bid to drive down costs and penetrate multiple markets. Assuming past learning rates continue, the best battery packs should become competitive with alternative energy applications by 2025[28]. However, it could be argued that basic extrapolation of learning rates is rather simplistic, since the costs of battery technologies are determined by factors such raw material costs and the fundamental physics of electrochemical processes, which may limit the ultimate potential for cost reduction[29]. This may push back the date of competitiveness with alternatives until the late 2020s. Of course, economics are not the only determinant of technology choice; aspects such as safety and portability can also play a role.

25 The range of capital costs for Li-ion batteries varies significantly due to variants in cell chemistry. These variants have different trade-offs between energy density, efficiency, safety, lifetime, etc.

26 For this reason, cost comparisons between batteries and other technologies should only be done on an application-specific basis.

27 Lazard November 2015

28 While battery costs have decreased significantly over the last years, inverter costs have not followed the trend due to lack of competition, and remain a large cost component of the battery storage solution for power-grid applications. The situation might change as OEMs seek to develop integrated solutions including inverters and put pressure on price.

29 In particular for batteries using lithium, limited resources might impact the costs in the long term.

4. Local regulation decisive in giving the boost to battery deployment

To date, much of the development in battery technology has been driven by the consumer device and, recently, in particular, automotive industries. However, the evolution of the energy market is rapidly escalating needs for storage technologies, meaning the power sector is likely to become a catalyst for cost reduction and technology development. Energy-market evolution calls for more flexibility in the network, which batteries can provide. The drivers for battery use in the power sector are discussed in more detail in the following section.

Fundamental drivers of battery storage

We have seen in the previous section that batteries can be used in various applications and by a broad range of market players.

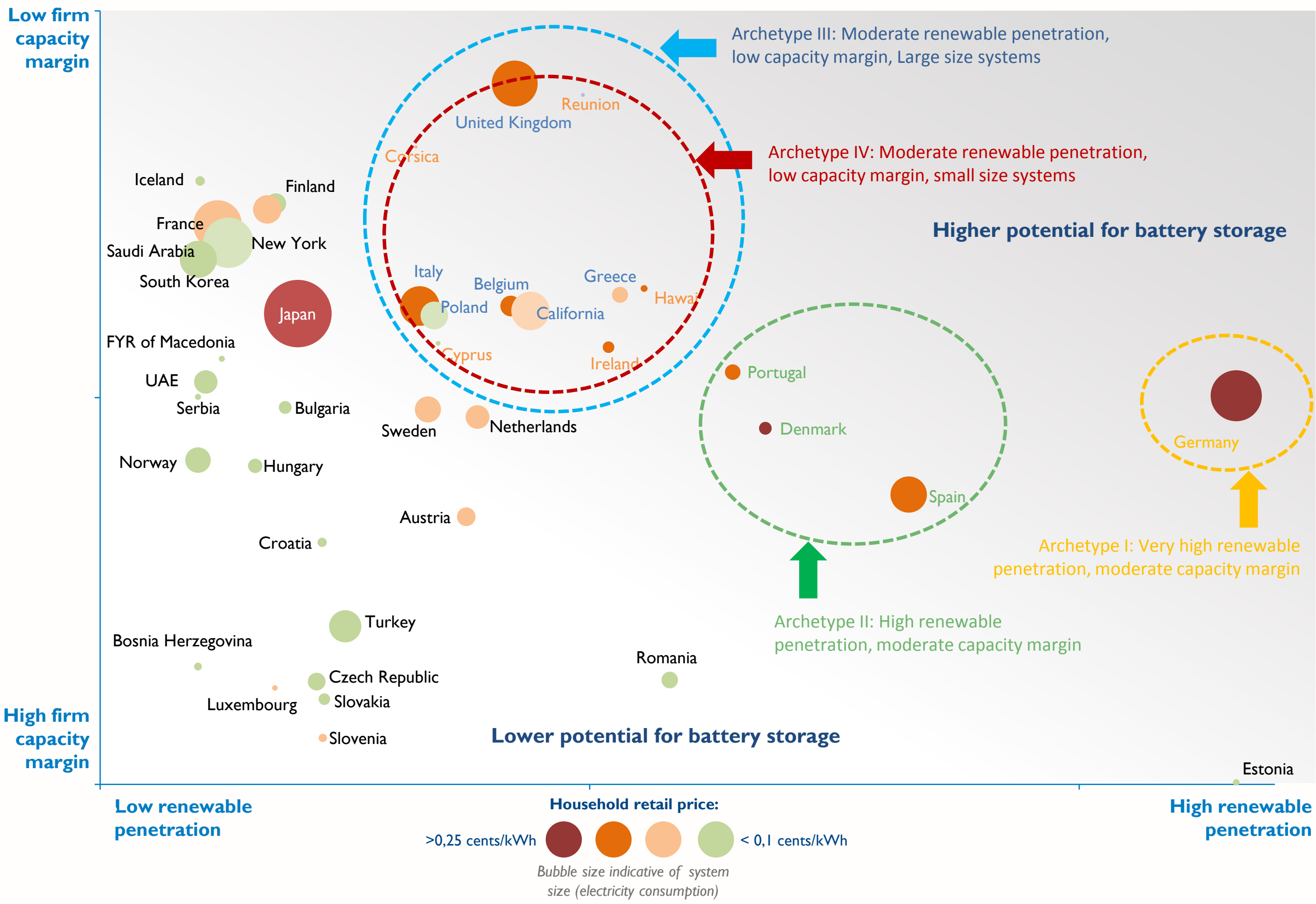
The flexibility offered by batteries becomes even more valuable as renewable energies develop and constrain system operation and planning. But renewable penetration is not the only parameter driving the business case for storage in particular markets. Table 1 summarizes the key drivers for storage deployment and the applications they directly address.

	Drivers	Rationale	Key applications
1	**High grid-renewables penetration**	▪ Need for further flexible generation to step in/out at short notice due to fluctuating, unpredictable power generation in the network ▪ *Tends to increase price differentials in the market through introduction of low marginal generation costs (see Driver 5)*	▪ Frequency response ▪ Frequency regulation ▪ Stable output
2	**Degree of physical decentralization of renewable generation assets**	▪ Pressure on the distribution network to accommodate new and unpredictable generation capacity in the network	▪ Frequency response ▪ Frequency regulation ▪ Stable output ▪ Voltage stability
3	**Tight flexible capacity margin**	▪ Reflects low flexibility in the system to accommodate intermittent renewables ▪ *Tends to go along with expensive generation at the margin, leading to high prices at peak periods (Driver 5) and high retail electricity prices (Driver 6)*	▪ Frequency response ▪ Frequency regulation ▪ Stable output
4	**Poor security of supply**	▪ Provision of enhanced security of supply with battery systems (coupled or not with renewables) at all times or during network outages	▪ Self-supply & TOU
	Enablers	**Rationale**	**Key applications**
5	**High peak/base-load price spread**	▪ Benefits the battery-storage business case by increasing revenues from charging/buying electricity during low price periods and selling/discharging during high price periods ▪ Price spread is closely related to the generation mix, including renewable share and capacity margin	▪ Arbitrage
6	**High electricity retail prices**	▪ Incentives for optimized self-production through a combination of self-generation (from PV, for example) and storage (e.g. store surplus for later usage)	▪ Self-supply & TOU

High renewable penetration (grid and distributed) and **tight flexible-capacity** margin have been identified as key drivers, conveying an indication of both flexibility needs and the underlying economics (e.g. price spread and retail prices).

A selection of countries have been mapped against these two drivers, allowing identification of high-potential countries for battery deployment, on Figure 5.

Figure 5: Countries mapped against key drivers of battery deployment[30]



This framework highlights groups of countries that face similar constraints, representing potential for battery deployment. Among these high-potential groups are countries at the forefront of storage development and deployment, such as **Italy, the United States (California), the United Kingdom and Germany**. On the other hand, other markets under similar conditions have, until now, only seen very limited development of batteries. This could be explained by:

- The development of alternative storage technologies (hydro-storage and pump-storage plants, CAES, flywheels, power to gas) and/or **alternative business models**, providing indirectly similar flexibility services (e.g. interconnection, distributed conventional generators, DSR). Despite high costs, key competitive advantages of battery storage compared to alternative storage technologies and business models are **rapid deployment**[31] (versus the development of connections, interconnections and hydro-storage) and **reliability** (versus demand-side management);
- Lack of strong political involvement to clarify the **regulatory framework** and **market mechanisms** and lack of willingness to bring down the major **cost barriers** left today. Examples of levers include **clarifying the role of TSOs and DSOs** related to storage, reviewing the **procurement of system** services (eligibility and combination of services) and reconsidering **taxes and fees** on storage to avoid double charging (load and generation).

30 Firm capacity margin evaluated based on installed intermittent capacity, incl. interconnection on peak demand; renewable penetration evaluated based on intermittent renewable installed capacity at peak demand
31 Hence the importance of energy and power density and module size
32 EENews, May 2015
33 Interconnection capacity represents about 20% of the peak demand

Deployment status, enablers and alternatives

Germany

Archetype I: Very high renewable penetration, high capacity margin

The German power system is characterized by high penetration of distributed (PV) and centralized (wind) renewable generation, and a booming residential storage market. Policy measures have been promoting hybrid distributed systems (PV + batteries) for more than two years now, in order to accommodate distributed renewable penetration in the grid. The **KfW programme 275**, for example, provided a 30% investment grant for equipment purchased with low-interest loans until the end of 2015 to residential customers who could see their on-site consumption increased with batteries[32]. While high retail prices also facilitate the business case for residential batteries, incentives are playing a key role in a market where the average state of charge of batteries approaches zero over the first three months of the year. Potential savings achieved with residential battery storage for self-consumption are fundamentally lower in Germany than in other markets, such as California, which benefits from favorable irradiation all through the year. However, this also presents opportunities for VIUs and system operators to use residential batteries as additional storage capacity over this period, as discussed in Section 3.

Compared to the residential sector, the industrial and commercial (I&C) sectors have so far lagged behind. And still, retail prices are high, capacity margin is decreasing with the closing of nuclear plants, and I&C-owned renewables are ever growing. But the incentives for German I&C are not there: network charges and tax regimes do not promote I&C storage. Furthermore, Germany's high interconnectedness with neighboring markets[33] means that excess supply is better sold to neighboring countries than stored and kept for self-consumption or for later hours in the day. In a nutshell, integrated power grids via interconnections lead to a smoothing impact on power-price spreads and volatility, which goes against part of the battery-storage business case.

Spain

Archetype II: High renewable penetration, high capacity margin

Battery deployment in Spain remains very limited despite a high share of renewables in the network. The government started cutting back on subsidies for renewables in the past five years, and the new self-consumption law adopted at the end of 2015 is expected to adversely impact residential battery storage. Under this new law, hybrid battery-storage owners will not be able to decrease their maximum connection capacity and therefore benefit from lower network charges. So although market fundamentals (e.g. high deployment of PV panels, relatively high retail prices) are present in Spain for the widespread development of residential battery storage for self-consumption, the absence of incentives slows down the deployment of battery storage.

32 EENews, May 2015
33 Interconnection capacity represents about 20% of the peak demand

United Kingdom

Archetype III: Moderate renewable penetration, low capacity margin, large size systems

The United Kingdom is one of the key battery markets in Europe:

- Changes to the policy and regulatory landscape are ongoing to further support the deployment of batteries. The launch of a call for evidence was announced for summer 2016 to investigate ways to facilitate use of flexibility before a reform is proposed by Spring 2017.
- National Grid foresees 1GW of non-pumped storage by 2020, providing regulatory barriers are removed.
- In response to the flexibility challenges already faced today in the UK, National Grid ran the Enhanced Frequency Response auction during summer 2016, which resulted in 200 MW battery storage clearing the auction, with April 2017 as the earliest start date.
- In the Irish Single Electricity Market, where the share of renewables is higher than in the UK, AES recently commissioned a 10 MW battery to provide fast-response ancillary services, and initiated the first step of a planned 100 MW battery project[34].

On the other hand, the deployment of battery storage at the residential level remains limited in the UK: residential PV is less developed, battery prices are too high and subsidies are insufficient compared to the retail price.

Battery storage competes with other flexibility tools on the market such as interconnectors, flexible generation and demand-side management. Distributed conventional generators, in particular diesel generation, have lately had significant success with current grid challenges in the UK. Responding to market signals, distributed conventional generators are regaining interest with VIUs, generators and merchant players to generate revenues from capacity mechanism and ancillary services and reduced network charges (TRIADS).

About 1.1 GW[35] small-scale distribution connected generators cleared the capacity mechanism auctions, hoping to capture revenues not only from the capacity mechanism, but also through embedded benefits that include the avoidance of transmission network charges. Stand-alone batteries today did not succeed in clearing the CM auctions, and hybrid renewables/batteries so far have not been allowed to participate in it.

The UK government, through National Grid, is also supporting demand-side response as a tool to provide flexibility to the grid. In fact, demand-side response is increasingly seen as a potential contributor to frequency response through the intermediary of aggregators (more details in *ADL's Viewpoint on Demand Side Management - Untapped Multi-Billion Market for Grid Companies, Aggregators, Utilities and Industrials?*). The business model consisting of incentivizing end consumers to reduce their consumption or switch to behind-the-meter generators to respond to grid requirements has been widely tested and enabled through regulatory changes. But the extent to which operators could rely entirely on third-party response and substitute assets, providing flexibility with DSR, has not been fully proven yet[36].

Demand-side management is not necessarily competing with storage applications, and can actually be complementary to storage when flexibility from Demand Side Management is not available. In fact, batteries could be used as a complement to behind-the-meter generators (e.g. hybrid generators) and activated through demand-side response.

34 National Infrastructure Commission, UK, 2016
35 Ofgem, June 2016
36 UKPN study

United States

Archetype IV: Moderate renewable penetration, low capacity margin

Activity in the battery storage market in the US is highly dependent on the state. California is one of the states with the highest renewable capacity (wind and solar), and a leader in battery storage deployment. Its 30% penetration rate of renewables and 70%–30% split of solar capacity between utility-scale solar and distributed PV has driven the deployment of battery storage at both grid and residential levels.

Beyond favorable fundamentals, the deployment of battery storage is supported by relatively high residential tariffs and strong regulatory signals, with California's Public Utilities Commission setting clear targets that require utilities to build energy-storage capacity and clarifying the market rules for behind-the-meter battery aggregation. Southern California Edison (SCE) acted as first mover and bought 261 MW of energy storage by the end of 2014, 100 MW of which were from AES and 85 MW from Stem (both battery storage). Stem also recently won close to 1MW capacity in the demand-side response (DSR) auction held this summer by Con Edison for the state of New York, testifying to the complementarity of battery storage and DSR.

The state of New York is also one of the early adopters of battery storage, and currently clarifying market rules for enabling battery storage to access the market.

In the PJM (Regional Transmission Operator, part of the Eastern Interconnection grid), the creation of fast regulation reserve combined with pay-for-performance framework introduced by the Federal Energy Regulatory Commission have promoted the development of battery storage with about 250 MW[37] energy storage (flywheel and battery storage) installed to date. However the decrease in clearing prices, namely due to falling oil prices, have raised concerns on the economics of battery storage.

Other parts of the United States, such as the Northwest, will likely be later adopters given their significant hydro-resources and the flexibility provided by hydroelectric and pump storage, which are sufficient to manage current levels of renewables.

Archetype IV: Moderate renewable penetration, low capacity margin, small-size systems

Island markets: Spain, Greece, France, Italy, UK

Island markets have seen a lot of activity in battery storage. The unique challenges faced improve the business case for battery storage: networks are more quickly saturated given their smaller grid size and higher generation costs driven by more expensive generation mixes (e.g. diesel generators). Battery storage is an opportunity for these markets to support the development of renewable energies, support decarbonization of markets often heavily reliant on oil-fired generation, decrease exposure to oil prices and potentially reduce costs. Island markets also have fewer available alternatives to add flexibility to their systems: pump-storage plants are often not an option, and interconnection is weak if existent. So it is with no surprise that most countries have concentrated their pilots on these islands when possible: La Gomera and La Aldea de San Nicolas (Canary Islands) in Spain, Azores (Graciosa Island) in Portugal, Tilos in Greece, La Réunion in France, Sardinia and Sicily in Italy, and Hawaii.

Pilots have so far focused on grid-scale batteries within hybrid configurations or stand-alone providing support to the grid to enable renewables integration.

In Hawaii, where about 90% of solar capacity is distributed PV, HECO recently announced it would finance and deploy residential storage to resolve grid congestion and enable more distributed PV to connect to the grid. This is one of the few examples where utilities are paying for and remotely operating residential storage. A couple of grid-scale hybrid configurations have also been announced: Ambri battery storage next to a wind farm on Oahu's North Shore, and SolarCity's solar PV battery project on Kaua'i.

Some islands have made energy storage mandatory for every new renewables plant in the system in order to better manage intermittency: Puerto Rico, La Réunion, Guadeloupe, Martinique and Azores.

37 Resilient Power, PJM, February 2016

5. Fast move for some, wait for others – shape for all

Battery storage is expected to play an important role in responding to the current challenges posed by the deployment of renewables.

However, today there are a number of barriers to its implementation, such as regulatory uncertainty, commercial arrangements, maturity of technology and associated costs.

In the short term, the deployment of battery storage in specific markets will depend not only on market characteristics (e.g. renewables penetration, interconnectedness, generation mix, the network's topology and system size), but also the regulatory framework, incentives and commercial signals in place to enhance the battery storage business model:

- **Grid-scale storage** for **frequency regulation** and **stable output applications** are seen as the most promising[38] applications today. While it has significantly developed in countries such as Japan, the US (California) and Germany, residential battery storage comes only third because of the difficulty of building a positive business case without strong support from public policies;
- In most countries (except Italy) system operators are restrained from developing battery storage solutions beyond pilots because of the regulatory definition of battery storage and the role the regulator expects from a system operator to play;
- The combination of applications is essential today to stack revenue streams and build a positive business case. Current market design (definition of ancillary services, access to grid services and the possibility of stack services) is often not adapted to make the most of battery storage;
- Even if the regulatory framework is clarified and system operators are allowed to own and operate batteries, the business case will continue to be challenging in the short to medium term to provide the sole grid-support services. Combined ownership is considered the most likely, economically viable solution for system operators.

So is it too early for battery storage?

- For **residential hybrid PV/storage,** current commercial developments show that the opportunity is now **where proper incentives are in place**. In leading markets such as Germany and California, VIUs already differentiate themselves and enter the battery storage market to broaden their offerings. VIUs are not alone in this market, and the role of aggregators continues to expand and evolve to cover battery storage, either as software providers or technology operators, though somewhat slowed down by the evolving regulatory framework, their access to ancillary services and energy market;
- For grid-scale applications, it is time for **early adopters**. **Power utilities** are stepping into the market and a series of large-scale commercial battery storage contracts have been announced over the last year. The majority of these contracts will provide flexibility services (e.g. frequency response, frequency regulation) to the grid and benefit from arbitrage. **Island markets**, under the initiative of system operators, have been leading the market in terms of grid-scale battery deployment (combined with renewables to stabilize output or for frequency regulation) by power utilities and, in some particular cases, directly by system operators;
- The deployment of battery storage by industrial and commercial customers is likely to remain limited in the short term given the current challenging economics, with the exception of the telecom industry presenting particular challenges related to accessibility and security of supply;
- **System operators** have so far been very cautious regarding the integration of batteries in their portfolios and limited themselves to pilots. The current regulatory framework and prohibitive costs have led batteries to be considered, if anything, an **asset of the future**.

Battery storage is a **fast move** today for some actors in the value chain and a **wait** for others, but for all it is a **market to shape** and a **strategy to develop** now if they don't want to turn up late at the party.

38 Applications that make the most economic sense today

"Battery storage is a fast move today for some actors in the value chain and a wait for others. But all actors can shape the market and must develop their strategy now if they don't want to turn up late at the party."

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Arthur D. Little has been at the forefront of innovation since 1886. We are an acknowledged thought leader in linking strategy, innovation and transformation in technology-intensive and converging industries. We navigate our clients through changing business ecosystems to uncover new growth opportunities. We enable our clients to build innovation capabilities and transform their organization.

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