IRENA
International Renewable Energy Agency

UTILITY-SCALE BATTERIES

INNOVATION LANDSCAPE BRIEF

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1 BENEFITS

Batteries can provide services for system operation and for solar PV and wind generators, defer investments in peak generation and grid reinforcements.

RENEWABLE GENERATORS

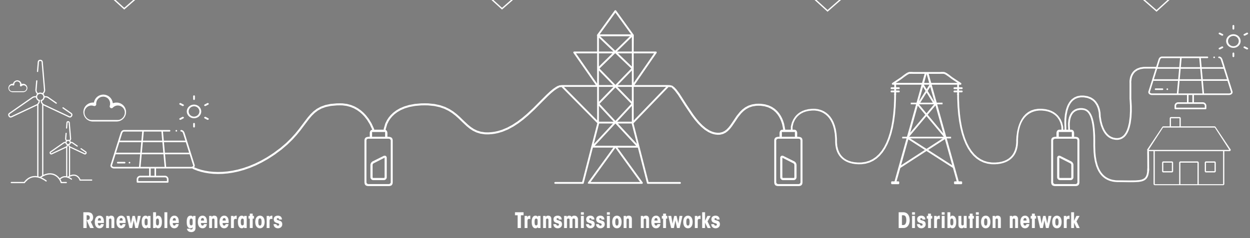
- Reduced renewable curtailment
- Renewable capacity firming

SYSTEM OPERATION

- Frequency regulation
- Flexible ramping
- Black start services

INVESTMENT DEFERRAL

- Transmission and distribution congestion relief
- Energy shifting and capacity investment deferral



2 KEY ENABLING FACTORS

- Reduced upfront costs
- Conducive regulatory framework
- Pilot projects and knowledge dissemination

3 SNAPSHOT

- 10 GW of battery storage is deployed globally (2017)
- Batteries with a total annual production of 27 MWh are providing ¼ of total enhanced frequency regulation capacity in UK.
- A demonstration project in US showed that a 4 MW/40 MWh battery can save USD 2 million in fuel costs and 400 hours of grid congestion.

WHAT ARE UTILITY-SCALE BATTERIES?

Stationary batteries can be connected to distribution/transmission networks or power-generation assets. Utility-scale storage capacity ranges from several megawatt-hours to hundreds. Lithium-ion batteries are the most prevalent and mature type.

UTILITY-SCALE BATTERIES

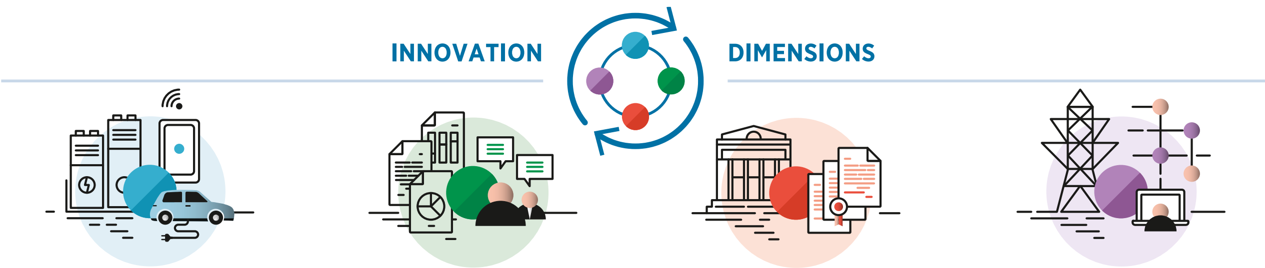
Battery storage **increases flexibility** in power systems, enabling optimal use of variable electricity sources like solar photovoltaic (PV) and wind energy.

ABOUT THIS BRIEF

This brief is part of the IRENA project "Innovation landscape for a renewable-powered future", which maps the relevant innovations, identifies the synergies and formulates solutions for integrating high shares of variable renewable energy (VRE) into power systems.

The synthesis report, *Innovation landscape for a renewable-powered future: Solutions to integrate variable renewables* (IRENA, 2019), illustrates the need for synergies among different innovations to create actual solutions. Solutions to drive the uptake of solar and wind power span four broad dimensions of innovation: enabling technologies, business models, market design and system operation.

Along with the synthesis report, the project includes a series of briefs, each covering one of 30 key innovations identified across those four dimensions. The 30 innovations are listed in the figure below.



ENABLING TECHNOLOGIES

1 Utility scale batteries
2 Behind-the-meter batteries

3 Electric-vehicle smart charging
4 Renewable power-to-heat
5 Renewable power-to-hydrogen

6 Internet of Things
7 Artificial intelligence and big data
8 Blockchain

9 Renewable mini-grids
10 Supergrids

11 Flexibility in conventional power plants

BUSINESS MODELS

12 Aggregators
13 Peer-to-peer electricity trading
14 Energy-as-a-service

15 Community-ownership models
16 Pay-as-you-go models

MARKET DESIGN

17 Increasing time granularity in electricity markets
18 Increasing space granularity in electricity markets
19 Innovative ancillary services
20 Re-designing capacity markets
21 Regional markets

22 Time-of-use tariffs
23 Market integration of distributed energy resources
24 Net billing schemes

SYSTEM OPERATION

25 Future role of distribution system operators
26 Co-operation between transmission and distribution system operators

27 Advanced forecasting of variable renewable power generation
28 Innovative operation of pumped hydropower storage

29 Virtual power lines
30 Dynamic line rating

This brief provides an overview of utility-scale stationary battery storage systems -also referred to as front-of-the-meter, large-scale or grid-scale battery storage- and their role in integrating a greater share of VRE in the system by providing the flexibility needed. The brief highlights some examples of large-scale battery storage deployment and the impact of this technology on the power system.

The brief is structured as follows:

I. DESCRIPTION

The growing share of VRE sources, such as solar and wind, calls for a more flexible energy system to ensure that the VRE sources are integrated in an efficient and reliable manner. Battery storage systems are emerging as one of the potential solutions to increase system flexibility, due to their unique capability to quickly absorb, hold and then reinject electricity. According to the Energy Storage Association of North America, market applications are commonly differentiated as: in-front of the meter (FTM) or behind-the-meter (BTM).

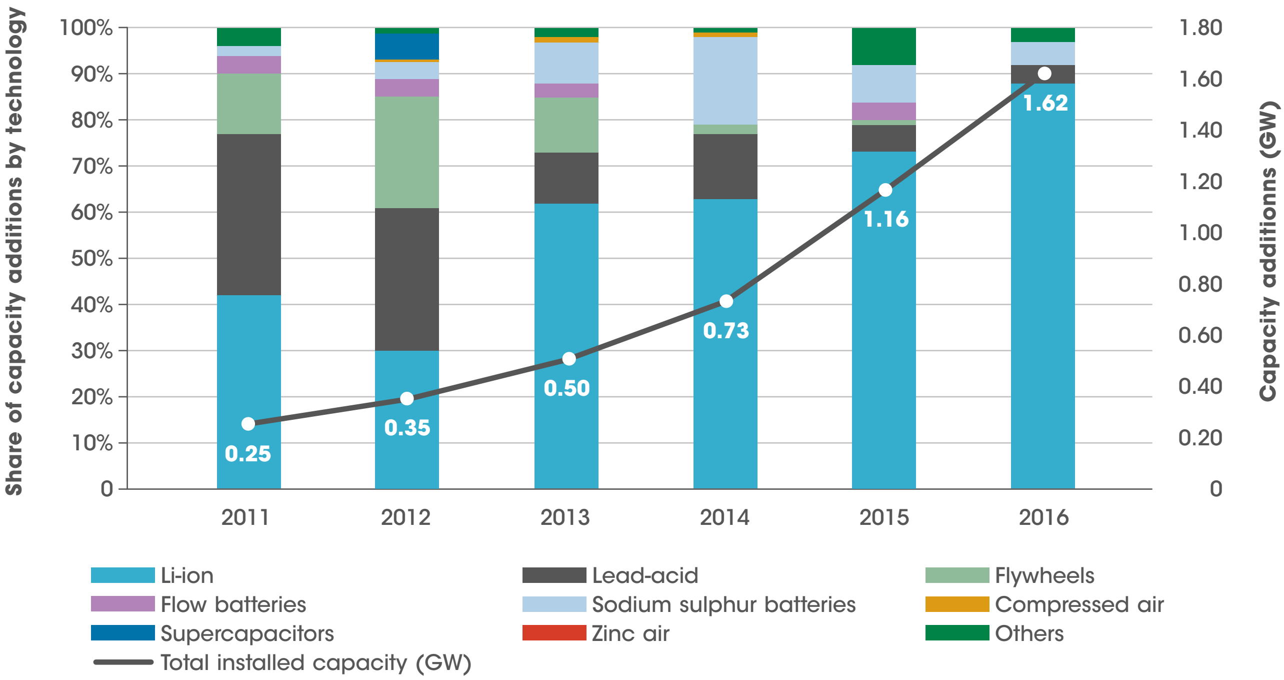
FTM batteries are connected to distribution or transmission networks or in connection with a generation asset. They provide applications required by system operators, such as ancillary services or network load relief. BTM batteries are interconnected behind the utility meter of commercial, industrial or residential customers, primarily aiming at electricity bill savings through demand-side management (ESA, 2018). This brief focuses on how utility-scale stationary battery storage systems – also referred to as front-of-the-meter, large-scale or grid-scale battery storage – can help effectively integrate VRE sources into the power system and increase their share in the energy mix.

Unlike conventional storage systems, such as pumped hydro storage, batteries have the advantage of geographical and sizing flexibility and can therefore be deployed closer to the location where the additional flexibility is needed and can be easily scaled. Deployment of pumped hydro storage, on the other hand, requires specific geological conditions (*i.e.* mountains and water).

Utility-scale battery storage systems have a typical storage capacity ranging from around a few megawatt-hours (MWh) to hundreds of MWh. Different battery storage technologies, such as lithium-ion (Li-ion), sodium sulphur and lead acid batteries, can be used for grid applications. However, in recent years, most of the market growth has been seen in Li-ion batteries.

Figure 1 illustrates the increasing share of Li-ion technology in large-scale battery storage deployment, as opposed to other battery technologies, and the annual capacity additions for stationary battery storage. In 2017, Li-ion accounted for nearly 90% of large-scale battery storage additions (IEA, 2018).

Figure 1: Increasing share of Li-ion in annual battery storage capacity additions globally

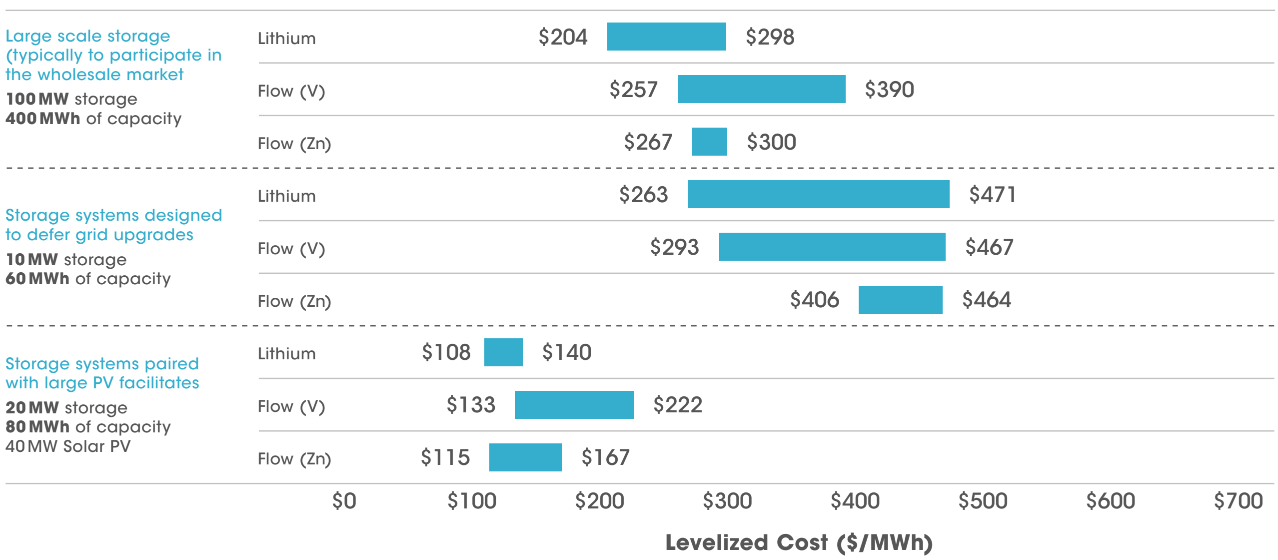


Note: GW = gigawatt
Source: IEA (2018); Sandia Corporation (2018)

The increasing share of Li-ion batteries in storage capacity additions has been largely driven by declining costs in Li-ion technology, which has in turn been driven by the ramp-up in production to meet growing demand for electric vehicles.

Figure 2 depicts the current levelised cost of three storage technologies (Li-ion, flow battery–vanadium, flow battery–zinc bromide) for three battery sizes, aimed at different applications:

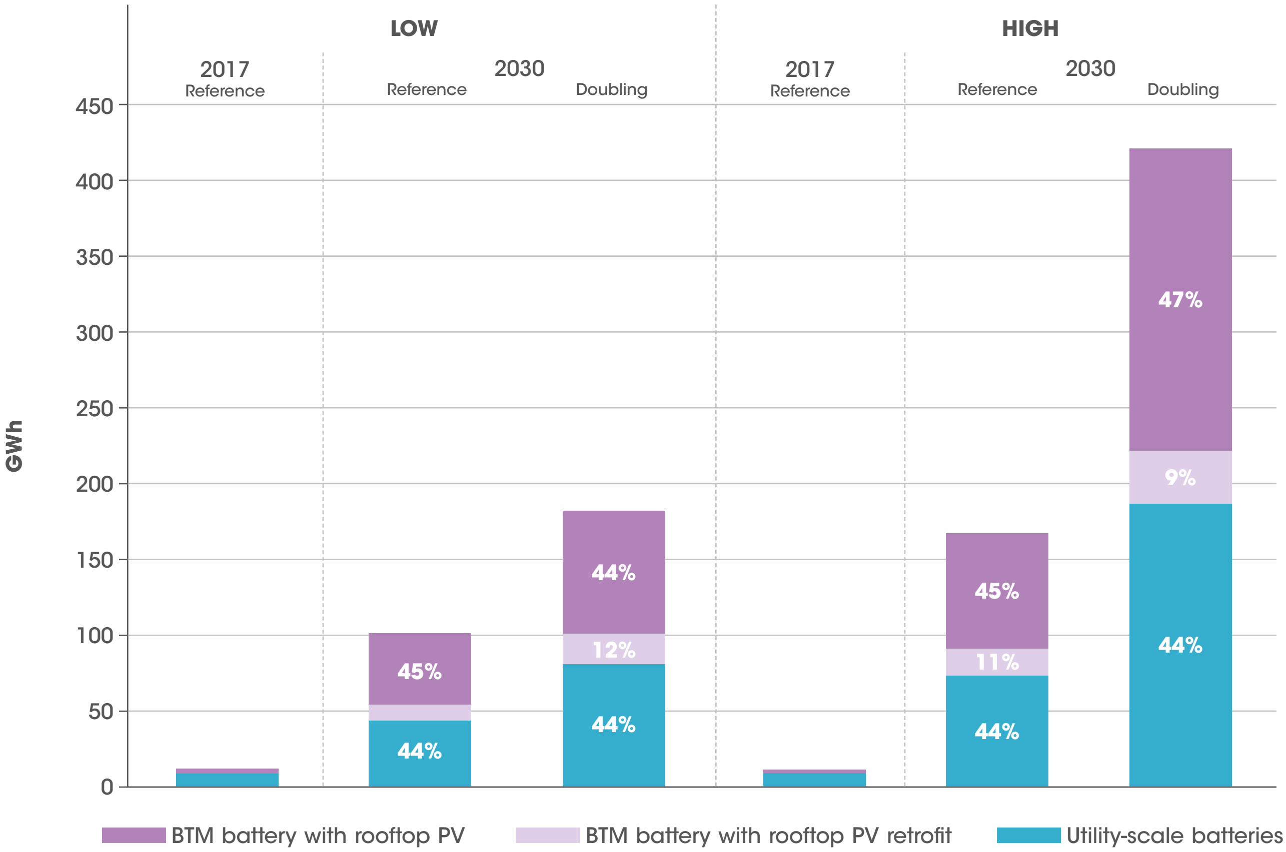
Figure 2: Comparison of levelised cost of storage (USD/MWh)



Note: Flow (V) = flow battery-vanadium; Flow (Zn) = flow battery-zinc bromide
Source: Lazard (2018)

Although large-scale stationary battery storage currently dominates deployment in terms of energy storage capacity, deployment of small-scale battery storage has been increasing as well. Figure 3 illustrates different scenarios for the adoption of battery storage by 2030. "Doubling" in the figure below refers to the scenario in which the stationary battery storage increases in response to the requirement to double renewables in the global energy system by 2030.

Figure 3: Stationary battery storage's energy capacity growth, 2017–2030

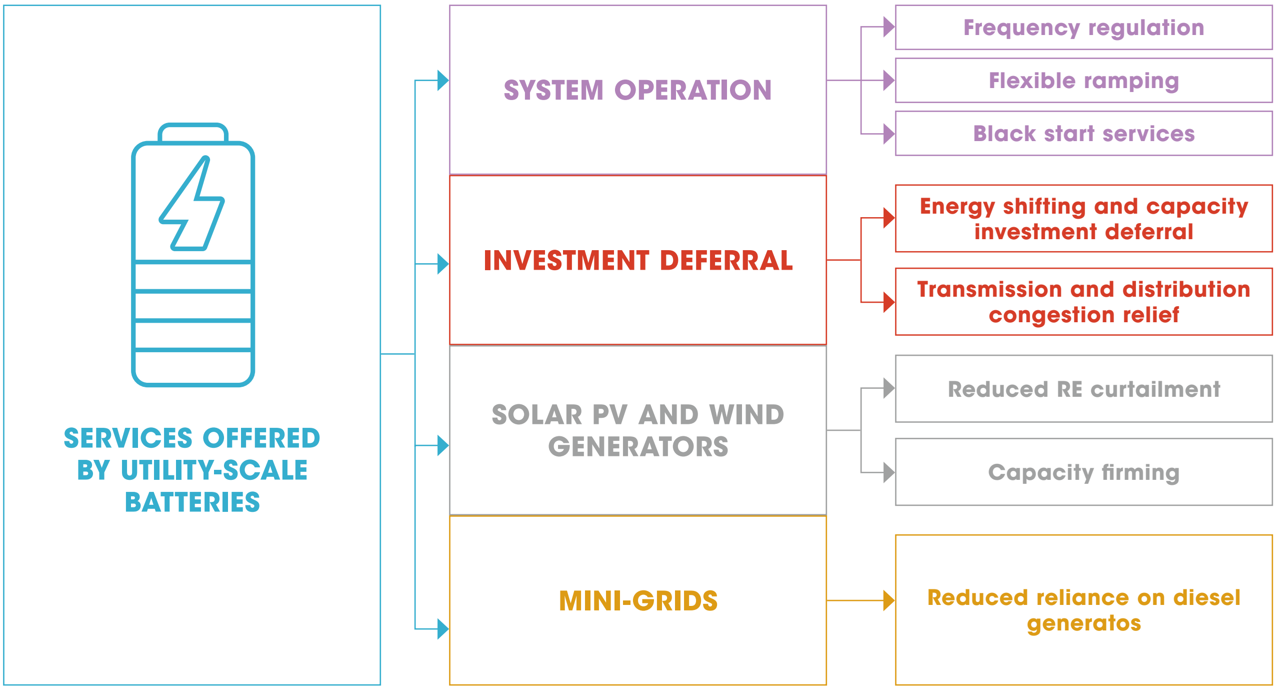


Note: GWh = gigawatt-hour; PV = photovoltaic; BTM = behind-the-meter
Source: IRENA, 2017

II. CONTRIBUTION TO POWER SECTOR TRANSFORMATION

Utility-scale battery storage systems will play a key role in facilitating the next stage of the energy transition by enabling greater shares of VRE. For system operators, battery storage systems can provide grid services such as frequency response, regulation reserves and ramp rate control. It can also defer investments in peak generation and grid reinforcements. Utility-scale battery storage systems can enable greater penetration of variable renewable energy into the grid by storing the excess generation and by firming the renewable energy output. Further, particularly when paired with renewable generators, batteries help providing reliable and cheaper electricity in isolated grids and to off-grid communities, which otherwise rely on expensive imported diesel for electric generation. Figure 4 summarises the key services offered by utility-scale batteries.

Figure 4: Services offered by utility-scale battery storage systems



Services provided for system operation

Utility-scale battery storage systems can provide key services that are needed for the operation of a system with high shares of VRE. These services include frequency regulation, flexible ramping and black start services, which are outlined below.

Frequency regulation

An imbalance between the power supply and the power demand can lead to a dip or a rise in grid frequency beyond the specified limits. Traditionally, thermal power plants have provided frequency control services. This can be inefficient and costly as it requires many generation plants to be either on standby or forced to run at capacity levels that do not use fuel efficiently, thereby increasing electricity costs. Utility-scale battery storage systems can provide frequency regulation services. As opposed to conventional plants that can take several seconds to minutes to respond to system operators' instructions, battery storage systems can typically respond to such requirements within milliseconds.

Tesla, a US company, commissioned the world's largest Li-ion battery storage capacity of 100 MW/129 MWh at the 315 MW Hornsdale Wind Farm in South Australia to provide contingency reserves and frequency regulation services to the South Australia grid. A report from the Australian Energy Market Operator states that frequency regulation services provided by this project are both rapid and precise, being comparable to services provided by conventional synchronous generation units (AEMO, 2018).

In the United States, Federal Electricity Regulatory Commission (FERC) Order 755 has mandated a separate compensation structure for fast-acting resources such as batteries, than for slower-acting conventional resources. This incentivised the use of battery storage systems to provide frequency regulation. This rule has already been adopted by various system operators in the United States, including PJM (Pennsylvania New Jersey Maryland), MISO (Midcontinent Independent System Operator), NYISO (New York Independent System Operator) and CAISO (California Independent System Operator), thus providing incentives to large-scale battery storage project developers (NY-BEST, 2016).

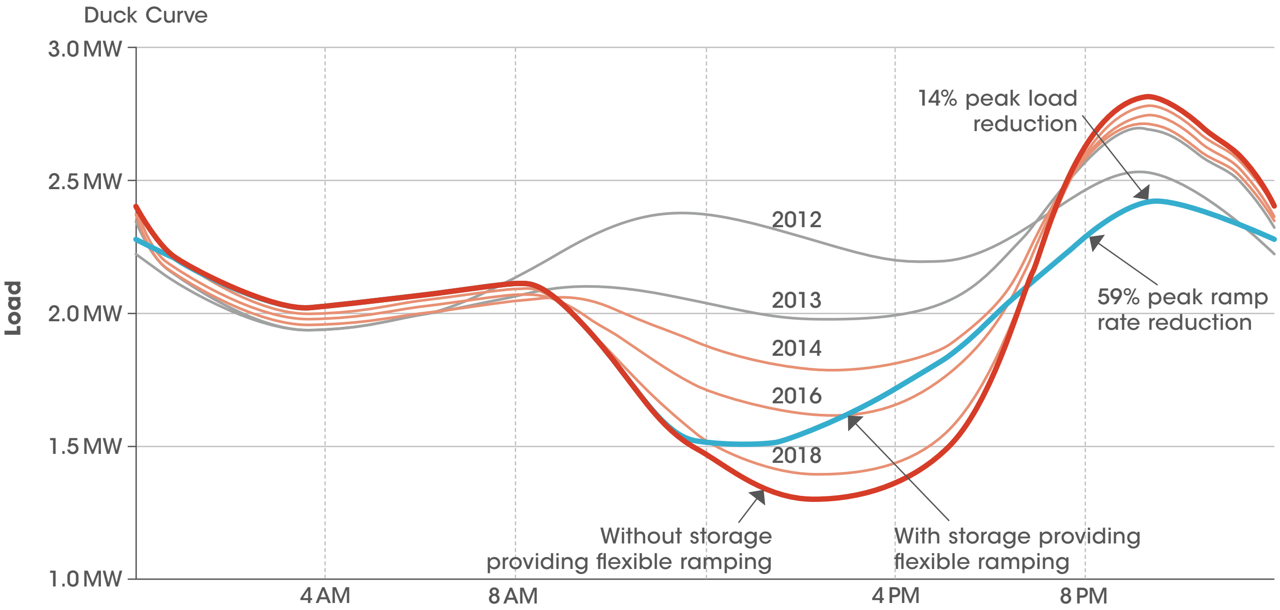
Similarly, the 2016 auction in the United Kingdom, National Grid, the transmission system operator, contracted 200 MW of battery storage capacity to enhance the frequency response capability over the next four years. Even though the tender for this project was technology neutral, battery storage systems won the entire capacity on offer as they were considered most suited for this application (KPMG, 2016).

Flexible ramping

When VRE penetration, and more specifically solar photovoltaic (PV) penetration, starts to increase, the shape of the load curve changes dramatically into the so-called solar duck curve. The duck curve is characterised by very high ramping requirements and was first prominent in the Californian power system. The system is required to ramp downwards in the morning when solar generation increases and ramp upwards in the evening when solar generation decreases and demand increases.

Flexible technologies such as utility-scale batteries would be suitable to help meet these ramping requirements and flatten the duck curve. For instance, California is fostering the deployment of energy storage systems and aiming to reach 1.3 gigawatts (GW) of newly installed storage by 2020 (California Energy Commission, 2018). Since 2016, CAISO has installed 80 MW of new battery storage systems, yielding a total of around 150 MW, including the largest Li-ion facility in North America at the time (30 MW/120 MWh), located in Escondido and owned by San Diego Gas and Electric utility (Davis, 2018). Figure 5 shows an expected effect on the duck curve of storage providing flexible ramping: 59% peak ramp rate reduction and 14% peak load reduction.

Figure 5: Impact on the duck curve of energy storage providing flexible ramping, using as an example a 3 MW feeder (not the entire CAISO system)



Source: Sunverge (2015)

Black start services

In the event of grid failure, restoration of generation plants requires power to start up again (referred to as "black start"). Typically, this restoration power is provided by diesel generators, which are co-located with the generating plants. Large-scale battery storage systems can be co-located, just like diesel generators, to provide black start services in cases of grid failure. Also, the battery storage systems installed on site could also provide other ancillary services to system operators when not being used to provide black start services. This would provide additional revenue to such battery systems.

Services provided for investment deferral

Energy shifting and capacity investment deferral

Large-scale battery storage systems are well suited to serve as capacity reserves as they can discharge during peak hours, displacing peak-generators and deferring further investment in peaking plants.

In the United States and Europe, large-scale battery storage systems are already being deployed to provide capacity reserves in commercial applications. For example, a 6 MW/10 MWh storage system was developed in Bedfordshire by a British distribution network operator, UK Power Networks, and is currently being operated by demand response software startup Limejump to provide capacity reserves in addition to grid-balancing services to the UK grid (Williams, 2017).

Additionally, most of the several hundred MW of utility-scale energy storage procured in California to date serves the state's four-hour peak capacity needs. The electricity supplier Southern California Edison uses a battery farm of 20 MW capacity to store energy and meet spikes in demand, for example on hot summer afternoons when buildings turn on the air conditioning. The battery is designed to discharge 80 MWh of electricity in four-hour periods (Fehrenbacher, 2017).

Transmission and distribution congestion relief

During peak demand hours, power flow through transmission and distribution networks may exceed the load-carrying capacity of such networks, leading to network congestion. Traditionally, system operators have addressed this issue by investing in distribution and transmission assets to increase their carrying capacity. However, when congestion occurs only in specific situations for a very limited period, investments in reinforcing the entire grid might not be the optimal solution. Instead of overbuilding transmission and distribution systems, energy storage systems located at congestion points can be used as "virtual power lines" to enhance the performance and reliability of the system. Utility-scale battery storage systems, as part of infrastructure, can be used to store energy from renewable energy generation to address peak demand exceeding the network capacity. Additionally, battery storage systems can provide instantaneous response to transmission-distribution network systems to manage any variability caused by generation from renewable energy sources.

Batteries could be controlled directly by system operators to provide an instantaneous response during the few hours each year when the existing network substations may be overloaded. Moreover, instead of upgrading the substation capacity from, for example, 10 MW to an oversized 15 MW, as it is generally done, system operators could instead procure the exact incremental amount of storage to meet demand forecasts. For instance, Italy's transmission system operator, Terna, deployed a pilot battery storage project of 35 MW on a part of its 150 kilovolt (kV) grid in Southern Italy for grid congestion management (Terna, 2018). Utility-scale batteries are also used for grid upgrade deferral in California, New York and Texas.

Services provided for VRE generators

Reduced renewable energy curtailment

VRE generators do not have a controllable fixed output, but a fluctuating, non-dispatchable one. Excess renewable energy generation curtailment – in times of high VRE generation and low demand – has been witnessed in some locations, resulting in a missed opportunity to integrate clean electricity into the energy mix. Grid constraints prevent transporting excess renewable energy generation to other regions leading to curtailment. Utility-scale battery storage systems are one of the solutions for reducing renewable energy curtailment. Excess electricity can be stored and then used at peak demand, when most needed.

Another emerging trend in large-scale battery storage is to deploy centralised batteries in a district to store the surplus energy generated by local distributed generation plants, such as rooftop solar PV. These battery storage systems are connected to the distribution network and can be directly controlled by the distribution system operator. The stored electricity can be utilised later when demand exceeds supply in the specific district. Such pilot is being implemented in Walldorf, Germany, with a 100 kW battery system connected to 40 households (GTAI, 2018).

Capacity firming

VRE generation is characterised by variability and uncertainty. Power fluctuations in solar PV generation are mainly caused by cloud movements, and fluctuations in wind power generation are provoked by the variability of wind speed. Coupling a specific VRE generation source with a battery reduces the variability of the power output at the point of grid interconnection, thus facilitating better integration of renewables. The battery storage system can smoothen the output of VRE sources and control the ramp rate to eliminate rapid voltage and power fluctuations in the grid. Further, the smoothening of generation would allow renewable energy generators to increase compliance with their generation schedules and avoid penal charges for any deviation in generation. Generation smoothening would also allow renewable energy generators to take better positions in market-based auctions for energy or capacity because it would increase the certainty and availability of round-the-clock power.

For instance, Acciona Energia has implemented a Li-ion battery storage system at the Barasoain experimental wind farm in Spain. The system comprises a fast response battery with a capacity of 1 MW/0.39 MWh that can maintain 1 MW of power for 20 minutes, and one slow response battery with greater autonomy of 0.7 MW/0.7 MWh that can maintain 0.7 MW for one hour. The batteries will store energy produced by the wind turbine when required (Froese, 2017).

Services provided to mini-grid systems: Reduced reliance on diesel generators

Mini-grid systems on islands or remote communities have typically relied on diesel generators for reliable energy supply. As energy generation from renewables has become cost competitive, their deployment on islands and remote areas is increasing. However, it is difficult to balance variable demand and supply in such remote areas because of the absence of flexible sources of generation. Battery storage systems can help back up the renewable energy supply in such situations and help balance the supply and demand by charging and discharging as needed. This will lead to decreasing dependence on diesel-based power in such systems and an increasing share of renewable energy generation.

In Hawaii, almost 130 MWh of battery storage systems have been implemented to provide smoothening services for solar PV and wind energy in addition to providing grid services. More battery storage systems are planned (Hawaii Electric Company, 2018). Further, the island of Ta'u in American Samoa used to rely on diesel to supply all its electricity, until Tesla installed a 1.4 MW solar and 0.75 MW/6 MWh storage system in 2016. Now the island almost exclusively uses solar energy, sometimes without turning on the diesel generator for months for supplemental electric generation (Muoio, 2016)

Potential impact on power sector transformation

Increased deployment of utility-scale battery storage systems can help integrate greater shares of VRE into the power system and realise cost savings for multiple stakeholders. Renewable energy generators can increase revenues that would have otherwise been lost owing to curtailment. Islands and off-grid communities can further save on high fuel costs and reduce their fossil fuel dependency. Examples of such benefits are shown below

- A high-level demonstration study for mitigating transmission congestion using a 4 MW/40 MWh battery storage system showed that NYISO could save up to **USD 2.03 million in fuel costs and reduce almost 400 hours of congestion (IEEE, 2017)**.

- A draft study commissioned by the State of New York estimated over **USD 22 billion in savings** if the state deployed about 11 500 MW of energy storage in lieu of traditional grid solutions by 2025 (NYSERDA, 2018).

- PJM has deployed energy storage systems that are providing cost-efficient frequency response and reducing the use of fossil fuel generation for ancillary services. PJM has forecasted that a **10–20% reduction in the procurement of frequency response capacity could result in savings of USD 25–50 million** for its consumers (HDR, 2017).

- In 2014, Aquion Energy, a US energy storage system provider, completed the installation of a 1 MWh battery system as part of an off-grid solar microgrid at Bakken Hale on the island of Hawaii. This is expected to **reduce the fossil fuel usage** of the local community in Bakken Hale **by 97%** (ESA, 2014).

- In Martinique, the output of a solar PV farm will be supported by a 2 MWh energy storage unit, so that electricity will be injected into the grid at constant power, limited to 40% of the rated PV power. This will establish **solar PV as a predictable and reliable part of the island's energy mix**, with no need for additional back-up generation to compensate for the intermittent nature of renewable energy sources (DOE Global Energy Storage Database, 2019).

III. KEY FACTORS TO ENABLE DEPLOYMENT

Numerous factors are limiting the growth of the large-scale battery storage market worldwide. Utility-scale battery storage technologies have high upfront costs. Further, since utility-scale battery storage is an emerging technology, key stakeholders such as governments, regulators, system operators, generators and financiers are not completely aware of its benefits and case studies. As a consequence, they have not fully updated planning, valuation, procurement and interconnection processes to accommodate this new asset class.

Also, regulatory constraints, due to regulation not taking this technology into account, further limit the revenue streams and deployment of utility-scale batteries. It is therefore important to tackle these barriers by addressing them through government initiatives, incentive programmes and knowledge dissemination. This section lists some of the key enabling factors that could lead to faster deployment of large-scale battery storage systems.

Reducing upfront investment costs and the economic viability gap

Upfront investment costs are still a barrier to the growth of the large-scale battery storage market. Despite the significant reduction in cost of several battery technologies, the upfront costs for deploying large-scale battery storage systems remain high for most stakeholders. Local and national governments can stimulate demand by providing subsidies to battery storage owners, which would scale up deployment and reduce the upfront cost burden.

In most cases, although the monetisable and non-monetisable benefits combined outweigh the costs, the monetisable benefits are less than the costs, making the project economically infeasible for the project developer or owner. The difference between the cost and the monetisable benefits, or the economic viability gap, if greater than zero, might be due to high storage capital costs or unfavourable market mechanisms (IRENA, forthcoming).

Policy incentives to make up for the economic viability gap of electricity storage projects could be similar to those used to support VRE deployment in its early stages of development. These incentives could include capacity payment, grants, feed-in-tariffs, peak reduction incentives, investment tax credits or accelerated depreciation (IRENA, forthcoming).

In the United States, incentives provided under the American Recovery and Reinvestment Act of 2009 opened a new source of financing for large-scale battery storage owners. From 2009 to 2014, 124 grid-scale energy storage projects were commissioned to demonstrate several principal application categories, including battery storage for utility load shifting, ancillary services and distributed storage for grid support (Hart & Sarkissian, 2016).

Creating a conducive regulatory framework to value energy storage

Regulation needs to be adapted to take into account this new technology and market player, as well as the services it can provide to the system.

The existing grid system is designed to balance supply and demand, separating generators and load as distinct entities. In electricity storage, the roles of injecting energy and of absorbing or consuming energy overlap, making it difficult for storage to fit into existing market frameworks (IRENA, forthcoming). Clear regulations defining the ownership and operating models can enable a wide range of revenue streams for storage providers. This can include participation in wholesale electricity markets or the sale of frequency response or ramping services to system operators.

Energy storage plays a key role in the transition towards a carbon-neutral economy and has been addressed within the European Union's "Clean energy for all Europeans package". The role of batteries in balancing power grids and saving surplus energy represents a concrete means of improving energy efficiency and integrating more renewable energy sources into electricity systems. Batteries will also enhance energy security and create a well-functioning internal market with lower prices for consumers (European Commission, 2018). The "Clean energy for all Europeans package" intends to define a new regulatory framework that allows energy storage to compete fairly with other flexibility solutions, such as demand response, interconnections, grid upgrades and flexible generation.

At the national level, the electricity regulator in the United Kingdom, Ofgem, released the "Smart systems and flexibility plan" in July 2017. This plan aims to remove barriers for smart technologies such as energy storage. Some of the targeted interventions include:

- defining energy storage as a subset of the generation asset class
- modifying licence charges to exempt storage systems from final consumption levies
- bringing clarity to the co-location of storage with renewable energy generation plants without impacting existing agreements such as "Contracts for difference and feed-in-tariffs" (Ofgem, 2017).

Since 2011 in the United States, FERC Order 755 has mandated that regional transmission organisations and independent system operators pay storage asset owners for providing ancillary services such as frequency regulation (Wesoff, 2013). Further, in February 2018, FERC passed Order 841, requiring that wholesale market operators allow storage to provide every market product that the resources are physically capable of providing, namely capacity, energy and ancillary services. Within the subsequent nine months, each regional transmission organisation and independent system operator was required to prepare a plan for revising the tariff structure to establish a participation mode for energy storage (FERC, 2018). Further, FERC Order 845 has revised the definition of "generating facility" to include electricity storage explicitly. The order revises interconnection rules and protocols for storage. It also includes a set of provisions that should enable energy storage to utilise spare capacity on the transmission system (Maloney, 2018).

It is also essential that energy storage resources are evaluated and integrated in planning procedures, along with traditional grid investments and generation.

Establishing pilot projects and disseminating knowledge

For any emerging technology such as battery storage, pilot projects are essential in understanding the performance of the technology and producing key learnings for its successful scale-up. Countries without significant deployment of utility-scale battery storage projects can fund pilot programmes to evaluate the technical performance as well as assess different business models for battery storage systems. For example, a South African company has secured a grant from the US Trade and Development Agency to develop a pilot project that demonstrates the performance of an energy storage system. The project will test the performance of a large-scale energy storage system under South Africa's electric grid conditions (ESI Africa, 2017).

Another innovative pilot for mobile storage is being conducted in New York City: Consolidated Edison, a New York utility, is building a 1 MW/4 MWh demonstration project in the city, in collaboration with NRG Energy, to demonstrate multiple uses for battery systems. These batteries will be housed on tractor trailers and will be moved near distribution nodes experiencing peak load to relieve distribution constraints (Maloney, 2017).

IV. CURRENT STATUS AND EXAMPLES OF ONGOING INITIATIVES

Total battery capacity in stationary applications could increase from a current estimate of 11 GWh to between 100 GWh and 167 GWh in 2030 in the IRENA's REmap[1] reference case and to as much as 181–421 GWh in the REmap doubling case[2]. This represents a nine- to 15-fold increase over the present in the REmap reference case and a 17- to 38-fold increase in the REmap doubling case.

Utility-scale battery storage systems are mostly being deployed in Australia, Germany, Japan, the United Kingdom, the United States and other European nations. Apart from these countries, several island and off-grid communities have invested in large-scale battery storage to balance the grid and store excess renewable energy. Energy storage deployments in emerging markets are expected to increase by over 40% year on year until 2025, resulting in approximately 80 GW of new storage capacity (IFC, 2017). The following table provides some key facts about global large-scale battery storage installations.

Table 1 Key facts about large-scale battery storage

Description	Key facts
Key regions where large-scale batteries are used (2017)	Australia, China, Germany, Italy, Japan, Republic of Korea, the United Kingdom and the United States
Global installed capacity of large-scale battery storage systems	10 GW (IRENA, 2017)
Main services currently provided	• Ancillary services, such as frequency response and voltage support • Capacity reserve • Renewable energy capacity firming and curtailment reduction • Reliable power supply to isolated grids • Deferral of transmission and distribution upgrades
Most established large-scale battery storage technology	• Currently, Li-ion batteries represent over 90% of the total installed capacity for large-scale battery storage (IEA, 2017) • Costs fell by 80% from 2010 to 2017 (IRENA, 2017)
Largest capacity project to date	In November 2018, PG&E in California awarded the world's two largest battery contracts to date, at 300 MW/2 270 MWh and 182 MW/730 MWh (Bade, 2018).
Examples of battery manufacturers	BYD, GS Yuasa, Hitachi, Kokam, LG Chem, NEC Energy, NGK, Panasonic, Saft, Samsung SDI, Sony, Toshiba

1 IRENA's global REmap roadmap in its "REmap Scenario" analyses the deployment of low-carbon technologies, largely based on renewable energy and energy efficiency, to generate a transformation of the global energy system with the goal of limiting the rise in global temperature to below 2°C above pre-industrial levels by the end of the century

2 The "doubling" scenario refers to the scenario in which the stationary battery storage increases relatively in response to meet the requirement of doubling renewables in the global energy system by 2030.

Some case studies representing different applications of large-scale battery storage systems across the globe are provided below.

Table 2 Case studies of different applications of large-scale battery storage systems

Utility-scale battery	Location	Service provided	Description
Tesla 100 MW/ 129 MWh Li-ion battery storage project at Hornsdale Wind Farm	South Australia, Australia	**Frequency regulation** **Capacity firming**	The battery is intended to provide contingency reserves and ancillary services to the Southern Australia grid (Brakels, 2018).
STEAG's 90 MW/120 MWh battery storage project	Germany	**Frequency regulation**	German energy company STEAG has installed an aggregated capacity of 90 MW/120 MWh battery storage at six different sites in Germany, each having a battery storage capacity of 15 MW/20 MWh. Batteries are connected to the grid at 10 kV and are intended to provide primary frequency control reserve for 30 minutes according to the requirements of the transmission system operator (STEAG GmbH, 2017).
38.4 MW/250 MWh sodium-sulphur battery by Terna	Italy	**Grid investment deferral** **Reduced RE curtailment**	Italy had an excess of wind generation, and the transmission capacity was not enough to transport all this energy to the north of the country, resulting in wind curtailments. In 2015, Terna installed the battery system to absorb the wind energy and use it during later periods with low wind demand, avoiding the need to invest in new transmission capacity. Additionally, this battery can provide services such as primary and secondary reserves, load balancing and voltage control (NGK, 2019).
NGK Insulators 34 MW/204 MWh sodium-sulphur battery storage system	Rokkasho, Aomori, Japan	**Capacity firming** **Reduced RE curtailment** **Ancillary services**	A 34 MW/204 MWh battery storage system was connected to a 51 MW wind farm in northern Japan. The batteries will store the excess renewable energy produced and sell it during peak hours. Further, the batteries will provide frequency regulation and serve as spinning reserves (IRENA, 2015).
1.5 MWh battery + 270 kW solar PV project implemented by Secretariat of the Pacific Community	Yap State, Federated States of Micronesia	**Reduced reliance on diesel generators in mini-grids**	A 1.5 MWh battery system, combined with a cumulative solar PV capacity of 270 kW was deployed over five islands of Yap State, encompassing ten mini-grids. The intended application provides energy access in some areas and displaces costly diesel generation in others (IRENA, 2015).
Low-carbon Li-ion battery in Glassenbury (40 MW) and Cleator (10 MW)	United Kingdom	**Frequency regulation**	These two projects were awarded during the UK auction in 2016 to provide enhanced frequency regulation. Glassenbury has an annual production of 20 MWh, while Cleator produces 7 MWh. Together they provide a quarter of the total enhanced frequency regulation capacity in the United Kingdom and help stabilise the frequency in the grid (Low Carbon, 2019).
AES-SDG&E 30 MW/120 MWh Li-ion battery storage project	California, United States	**Capacity firming** **Reduced RE curtailment** **Capacity investment deferral**	The US utility San Diego Gas & Electric developed a 30 MW/120 MWh Li-ion battery storage project near one of its substations in Escondido to store excess renewable energy production in the state and also serve as a capacity reserve (SDG&E, 2017).

Utility-scale battery	Location	Service provided	Description
2 MW/6 MWh battery storage in San Juan Capistrano	California, United States	**Grid investment deferral**	The battery system offsets the peak demand overload and avoids distribution upgrades. Additionally, this battery can participate in other ancillary services thanks to its control system (Greensmith, 2016).
Renewable Energy Systems and Utility of Ohio's 4 MW/2.6 MWh battery storage project	Columbus, Ohio, United States	**Frequency regulation**	Driven by FERC Order 755, which mandates that independent system operators pay storage providers for the performance of their systems, Renewable Energy Systems, a United Kingdom-based firm, built a 4 MW/2.6 MWh battery storage system to provide frequency regulation services to PJM, a regional transmission operator in the United States (RES, 2017).

RENEWABLE ENERGY POWER GRID

V. IMPLEMENTATION REQUIREMENTS: CHECKLIST

TECHNICAL REQUIREMENTS	**Hardware:** • Widespread adoption of utility-scale batteries in power systems. **Software:** • Battery management software to protect the battery and act as a site controller to implement the charging and discharging algorithms
POLICIES NEEDED	**Strategic policies could include:** • Incentives to make up for the economic viability gap of electricity storage projects • Inclusion of energy storage solutions in long-term capacity expansion plans • Funding for pilot or demonstration projects and dissemination of learnings from case studies
REGULATORY REQUIREMENTS	**Wholesale market:** • Allow large-scale battery storage systems to participate in ancillary services markets and be remunerated accordingly for all the services they can provide to support the system • Develop accounting, billing and metering methods for large-scale grid-connected battery storage systems • Incentivise long-term contracts to have a clearly defined revenue stream over the amortisation period of the project **Transmission and distribution system:** • Allow large-scale battery storage systems to participate in ancillary services markets and be remunerated accordingly for all the services they can provide to support the system • Deploy large-scale battery storage systems as a solution to reduce overall investments in generating capacity and network reinforcement
STAKEHOLDER ROLES AND RESPONSIBILITIES	**Regulators:** • Include storage batteries in the long-term plans of the system expansion, along with traditional grid and generation investments • Define clear regulations for the ownership and operating models of storage systems, to enable a wide range of revenue streams

ACRONYMS AND ABBREVIATIONS

CAISO California Independent System Operator

FERC Federal Electricity Regulatory Commission

Li-ion lithium-ion

MISO Midcontinent Independent System Operator

NYISO New York Independent System Operator

PJM Pennsylvania New Jersey Maryland

PV photovoltaic

VRE variable renewable energy

UNITS OF MEASUREMENT

GW gigawatt

GWh gigawatt-hour

kV kilovolt

kW kilowatt

MW megawatt

MWh megawatt-hour

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