Implementation of large-scale Li-ion battery energy storage systems within the EMEA region

Citation for published version (APA):
Killer, M., Farrokhseresht, M., & Paterakis, N. G. (2020). Implementation of large-scale Li-ion battery energy storage systems within the EMEA region. *Applied Energy*, *260*, Article 114166. https://doi.org/10.1016/j.apenergy.2019.114166

Document license:
TAVERNE

DOI:
10.1016/j.apenergy.2019.114166

Document status and date:
Published: 15/02/2020

Document Version:
Publisher's PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

- A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
- The final author version and the galley proof are versions of the publication after peer review.
- The final published version features the final layout of the paper including the volume, issue and page numbers.

Link to publication

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

- Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
- You may not further distribute the material or use it for any profit-making activity or commercial gain
- You may freely distribute the URL identifying the publication in the public portal.

If the publication is distributed under the terms of Article 25fa of the Dutch Copyright Act, indicated by the "Taverne" license above, please follow below link for the End User Agreement:

www.tue.nl/taverne

Take down policy
If you believe that this document breaches copyright please contact us at:

openaccess@tue.nl

providing details and we will investigate your claim.

Download date: 04. Oct. 2023

Applied Energy 260 (2020) 114166

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Implementation of large-scale Li-ion battery energy storage systems within the EMEA region

Marvin Killer[a,b], Mana Farrokhseresht[a], Nikolaos G. Paterakis[a,*]

[a] Department of Electrical Engineering, Eindhoven University of Technology (TU/e), PO Box 513, 5600 MB Eindhoven, the Netherlands
[b] Department of Electrical Engineering and Computer Science, Royal Institute of Technology (KTH), SE-100 44 Stockholm, Sweden

HIGHLIGHTS

- A Li-ion BESS market overview of Europe, the Middle East and Africa is presented.
- Existing Li-ion BESS use-cases are analyzed.
- Key drivers enabling the implementation of Li-ion BESS projects are discussed.
- Requirements and associated risk factors are evaluated.
- The future relevant technological developments and market trends are assessed.

ARTICLE INFO

Keywords:
Stationary storage use-cases
Distributed energy resources
Energy storage market overview
Lithium-ion battery
Renewable energies

ABSTRACT

Large-scale Lithium-ion Battery Energy Storage Systems (BESS) are gradually playing a very relevant role within electric networks in Europe, the Middle East and Africa (EMEA). The high energy density of Li-ion based batteries in combination with a remarkable round-trip efficiency and constant decrease in the levelized cost of storage have led to the recent boom of the technology. However, many of the potential applications of large-scale battery systems are not economically viable at this point in time. As a result, several BESS projects are being pushed by the industry towards specific niches which are based on revenue streams that can be rather complex than straightforward. The aim of this paper is to provide an overview of how large-scale Li-ion BESS are currently being implemented in the EMEA region, giving an answer to the following questions: what are the main use-cases of large-scale Li-ion batteries that are being implemented? What are the key factors that are enabling the deployment of BESS projects in the present markets? How can current tendencies be extrapolated to the future outlook of Li-ion BESS implementations? The large-scale energy storage market is evolving at a very fast pace, hence this review paper intends to contribute to a better understanding of the current status of Li-ion battery systems focusing on the economic feasibility that is driving the realization of Li-ion BESS projects in the EMEA region.

1. Introduction

1.1. Motivation

Large-scale BESS are gaining importance around the globe because of their promising contributions in distinct areas of electric networks. Up till now, according to the Global Energy Storage database, more than 189 GW of equivalent energy storage units have been installed worldwide [1] (including all technologies). The need for the implementation of large-scale energy storage systems arises with their advantages in order to support the penetration of renewable energy sources (RES), increase grid flexibility, ensure system reliability, enable the development of new energy business models, reduce the requirements for additional network interconnections and support distribution system operators (DSOs), as well as transmission system operators (TSOs) [2]. As for now, promises are high that energy storage systems will enable a large integration of RES within the electric networks [3].

Out of the distinct energy storage technologies, electrochemical batteries have been undergoing a large increase in number of implementations due to the fast decline in their cost, favorable performance and modularity. From a technical point of view, large-scale electrochemical BESS have two significant advantages over most

---

[*] Corresponding author.
E-mail address: n.paterakis@tue.nl (N.G. Paterakis).

https://doi.org/10.1016/j.apenergy.2019.114166
Received 25 June 2019; Received in revised form 23 October 2019; Accepted 13 November 2019

Nomenclature

BESS	Battery Energy Storage System
BMS	Battery Management System
BTM	Behind-the-Meter
BoP	Balance of Plant
CAPEX	Capital Expenditures
C&I	Commercial & Industrial
DER	Distributed Energy Resources
DSO	Distribution System Operator
EFR	Enhanced Frequency Response
EMEA	Europe, the Middle East and Africa
EPC	Engineering, Procurement and Construction
EV	Electric Vehicle
FCR	Frequency Containment Reserve
FFR	Firm Frequency Response
FTM	Front-of-the-Meter
HVAC	Heating, Ventilating and Air Conditioning
HV	High Voltage
IRR	Internal Rate of Return
LCOE	Levelized Cost of Electricity
LCOS	Levelized Cost of Storage
Li-ion	Lithium ion
LV	Low Voltage
MENA	The Middle East and North Africa
MV	Medium Voltage
OPEX	Operational Expenditures
PCS	Power Conversion System
PHES	Pumped Hydro Energy Storage
PoI	Point of Interconnection
PPA	Power Purchase Agreement
RES	Renewable Energy Sources
RfG	Requirements for Generators
SoC	State of Charge
SCADA	Supervisory Control and Data Acquisition
TSO	Transmission System Operator
UPS	Uninterruptible Power Supply
VPP	Virtual Power Plant

conventional energy generators present in electric networks. First, they are capable of providing a very fast response - chemical batteries can ramp up to full power (both discharge and charge) within milliseconds. Second, they present a lot of operational flexibility being able to easily change their mode of deployment within the limitations of battery power and energy capacity. Out of numerous electrochemical battery families, Li-ion based storage solutions are currently leading the market. The main reasons for this are a very high energy density in combination with an already existing technology knowledge because of their implementation in distinct applications and markets such as mobile phones and notebooks. These conditions have been accentuated with a significant research and development push - only within the last decade, prices have been reduced by a factor of ten and energy densities have doubled [4].

The specific qualities and advantages of Li-ion BESS lead to a broad range of distinct applications where they can potentially be beneficial, both FTM (Front-of-the-Meter) and BTM (Behind-the-Meter). These include: grid services, distribution and transmission system congestion management, renewable energy integration, arbitrage, peak shaving, microgrids and aggregation. However, the real-world implementation of large-scale Li-ion BESS does not cover all potential use-cases that are related to the listed applications because in their vast majority they do not present economic feasibility. Hence, the realization of large-scale Li-ion BESS projects is constrained by specific conditions that need to be met in order to build a profitable business case, which usually implies the necessity to combine two or more revenue streams [5]. Nevertheless, the nature of the added value that each of those revenue streams represents can be completely different for each use-case, and are not always based on present economic profitability. All in all, the practicability of large-scale Li-ion BESS is highly dependent on the geographical location as well as on the particular energy market design.

When thinking of large-scale energy storage projects, the most outstanding potential application is without a doubt energy time arbitrage - shifting production of energy generators to peak consumption periods would enable a large integration of RES [6]. Moreover, the possibility to mitigate side-effects (such as over-voltage) to allow large-scale introduction of residential renewable generators in distribution networks is appealing [7]. In reality, however, none of them is economically feasible at this point in time, hence the vast implementation of Li-ion BESS projects in Europe, the Middle East and Africa (EMEA) is focusing on very distinct applications. These can be rather complex than straightforward, not from a technical perspective, but in order to optimize revenue streams to foster their financial viability. The significant increase in Li-ion based BESS projects is occurring because of a very strong market push - the BESS industry is discovering new niches that enabled the implementation of outsize battery systems on a global scale. Up to date, the largest commissioned Li-ion BESS has a size of 129 MWh and was implemented at the Hornsdale power reserve in Australia in 2017 [8]. Moreover, the biggest signed Li-ion BESS project that is going to be built in California in 2020, is almost ten times as big with up to 1100 MWh [9]. This magnification of large-scale Li-ion batteries showcases the increasing relevance of energy storage systems within electricity networks.

The gradual implementation of Li-ion BESS in the EMEA region has been following an exponential growth during recent years with an annual increase of almost 50% [10]. This very fast pace shows a positive turnaround for the introduction of energy storage technologies in electricity networks to accelerate the establishment of renewable resources. From here on, the future outlook of large-scale Li-ion storage systems can diverge significantly from the present status. First, many of the current use-cases where Li-ion BESS are being deployed will shift towards new applications. The reason for this is that some of the present markets are expected to congest in the near future. Furthermore, new market opportunities will arise with the constant decrease in cost, energy storage policy changes and push towards new deployments. Second, the utilized technologies might undergo changes, not only because of the still ongoing improvements on Li-ion batteries, but also due to the emergence of new energy storage technologies for similar applications.

1.2. Relevant literature and contributions

Recently, a large number of relevant reviews and studies have been published focusing on stationary storage markets, technologies, applications, policies, and business cases. Several annual reports, such as the Solar Media energy storage opportunity review [11], the stationary storage report from the European Commission [12] and the European market monitor from the European Association for Storage of Energy [10], give a broad overview of installed energy storage capacity, prices, project examples, and future market forecast. Furthermore, [13] demonstrated a good approach to quantify existing storage markets in numerous European countries. Beyond a general market overview, many publications focused on analyzing and comparing distinct storage technologies, from a technological point of view [14–16], but also assessing the economic viability and costs within distinct applications such as [17] and [18]. With regard to technological specifications and developments of Li-ion batteries, [19] and [20] provided a detailed review of the state-of-the-art. When it comes to potential applications of stationary storage, numerous publications analyzed distinct technically feasible use-cases for Li-ion batteries from a global perspective such as [21] and [22], but also focused on specific use-cases such as frequency regulation [23] or capacity reserve [24]. Considering the regulatory framework, [25] provided relevant discussion points for the required policies within the European Union in order to ease the integration of storage technologies. Lastly, several publications focused on the economic business case of distinct energy storage use-cases or application stacking. Some reports, such as [26], showcased different markets, while others evaluated specific countries such as Germany [27] and [28], or the Netherlands [29].

The objective of the present review paper is to address several of the above-mentioned topics, creating a broad overview of the current market status of large-scale Li-ion BESS for the entire EMEA region, analyzing the existing use-cases. The geographical area has been selected as it represents a common geographical division used by large industries (including battery manufacturers), and the combination of European, Middle Eastern and African countries is often employed for energy storage market reviews [30], as well as scientific reports [31,32]. However, instead of solely evaluating the economic feasibility of specific applications and/or projects, the present work focuses on assessing the main causes, both in terms of monetized revenues and non-monetized value, which are responsible for the implementation of existing storage systems within the entire region. This is done from a market perspective, in order to understand the present and future development of Li-ion technologies. Hence, the main contributions of this paper can be summarized as follows:

1. A Li-ion BESS market overview in the EMEA region is presented.
2. Existing Li-ion BESS use-cases are analyzed.
3. The requirements and key drivers that enable the implementation of Li-ion BESS projects and associated risk factors are evaluated.
4. The future relevant technological developments and market trends are assessed.

2. State-of-the-art: Li-ion technology and applications

Li-ion based battery technologies have been present for many decades in areas such as portable electronic devices and power tools. However, just in recent years, they have gained presence in large-scale grid related applications, undergoing a big research push in order to improve energy density, cost reduction, charging speed and safety. Furthermore, constant advances are being made on the system level of large-scale batteries in order to enhance overall efficiency and the performance of control systems, power electronics, and HVAC (Heating, Ventilating and Air Conditioning). Now, taking into account the present status of the technology, this section focuses on the advantages and properties of Li-ion cells, the general layout of large-scale BESS, and the possible applications for stationary energy storage. Note that the objective of this section is to provide a high-level overview of the technology. The interested reader is referred to [33] for further descriptions and detailed specifications.

2.1. Li-ion battery cells

Li-ion cells are based on the same principle as most electrochemical battery units with a cathode, anode, separator, and electrolyte. The cathode is composed of a lithium metal oxide, the anode mostly of carbon (graphite), the separator of a porous polymeric material and the electrolyte of lithium salt dissolved in an organic solvent [34]. The existing Li-ion cell types are differentiated based on the lithium-ion donator in the cathode since this is the main component that determines the cell properties. When comparing lithium to other metals that are being used in energy storage technologies, it presents noticeable benefits since it is non-toxic, very light and electropositive. Nevertheless, it is also highly reactive which creates severe safety issues. Some of the main benefits and drawbacks of Li-ion cells are shown in Table 1 [19].

Table 1
Advantages and disadvantages of Li-ion battery cells

Strengths/Weaknesses
+ High specific energy and power
+ Long calendar and cycle life
+ High round-trip efficiency
+ Adequate operational temperature range
+ High reliability
+ Diversity with distinct chemistry
+ Low self-discharge rate
+ Satisfactory charging speed
– High capital cost
– Advanced BMS required
– Safety incidents with thermal runaway
– Material bottleneck
– Weak recovery and recycling

Without any doubt, the main advantage of Li-ion batteries is their high specific energy which can go up to 250 kWh/kg for commercially available products. This enables a significant size reduction that can be very beneficial for many applications - especially for portable devices. Furthermore, in combination with the high power capability, the technology has proven to be more than suitable for electric vehicles (EVs) and energy applications, both grid-tied as well as off-grid. Notwithstanding the beneficial technological advantages, Li-ion BESS also have two very significant drawbacks. First, Li-ion batteries are expensive, and even though the cost has been decreasing drastically during recent years, it is still quite high, making many of the possible use-cases in large-scale energy applications non-viable. Second, it is quite complex to build safe battery cells that contain lithium - additional measures are required to protect from thermal runaway incidents. So far this has been tackled by not using metallic lithium, but rather compounds that are able to donate lithium ions.

There are several distinct Li-ion battery cell types that are being implemented in different applications within the storage industry. The most mature configurations are listed below together with their predominant applications and can be distinguished based on the metal oxide that composes the cathode:

- Lithium Cobalt Oxide (LCO) - Portable electronic devices
- Lithium Manganese Oxide (LMO) - Medical equipment
- Lithium Iron Phosphate (LFP) - EV/ Grid storage
- Lithium Nickel Manganese Cobalt Oxide (NMC) - Power tools/ EV/ Grid storage
- Lithium Nickel Cobalt Aluminum Oxide (NCA) - EV/ Grid storage

Out of these, NCA, NMC and LFP are the main configurations that are considered for grid storage applications because of three key factors: high specific energy/power, durability and material availability. In comparison, LCO based Li-ion cells are by far the most mature technology due to their big success in the cellphone and laptop industry. However, they do not present an advantageous lifetime durability that is critical for grid storage use-cases. Moreover, cobalt is gradually becoming a scarce resource, whereby manufacturers tend to reduce and/or avoid relying on it. Nowadays, NCA and NMC are most commonly used in grid storage projects, whilst LFP cells, despite their lower specific energy, are very promising for future implementation due to high safety and very long durability. Up to date, according to global market share statistics, the main Li-ion cell manufacturers are *Panasonic Sanyo*, *CATL*, *BYD*, *LG Chem* and *Samsung*.

2.2. Large-scale BESS layout

The general layout of large-scale Li-ion BESS is composed of several subsystems that enable operation, control, thermal management and grid integration based on a modular configuration. The main included elements are the battery system, the coupling system and the grid connection which are represented in Fig. 1. These are very dependent on appropriate sizing in order to optimize the overall performance and revenues [35]. Furthermore, due to the degradation of Li-ion cells over time, large-scale BESS often require to be over-sized and/or include the possibility to re-stack, which is why the modularity of individual components is indispensable. Note that the implementation scope of each subsystem can vary depending on the BESS manufacturer, the engineering, procurement and construction (EPC) contractor, and the project environment.

The core of the Battery System is made up of battery packs - these usually represent the smallest modular battery component that is commercially available. Every battery pack includes then several modules that are set up at the same voltage level containing hundreds of small Li-ion cells each. The HVAC system is responsible to maintain the battery packs within the permitted operational temperature range. This is a very critical constituent since the required energy to operate the HVAC can have a notorious impact on the overall efficiency and performance of the BESS. Lastly, the battery management system (BMS) is the control system that manages the overall operation of the battery regarding energy, including charge/discharge rate, state of charge (SoC) limitations, the balance of plant (BoP), status monitoring and internal power electronics if applicable.

The System Coupling is composed of a power conversion system (PCS) that is required in order to adapt the output signal of the Battery System to the point of interconnection (PoI) with the grid. This usually includes a power inverter to adapt DC to AC as well as a transformer to step up the voltage in case the PoI is at medium voltage (MV) or higher. The inverter might be directly integrated in the battery system or deployed externally depending on the BESS architecture, which can be either module integrated or centralized [36]. Meanwhile, the step-up transformer is usually out of the BESS scope (enclosed battery system). In addition to the PCS, the System Coupling does also include all physical lines and/or cables as well as protection schemes.

Grid integration refers to all the components that enable the interaction with adjacent systems. These can be directly connected loads, renewable energy sources such as PV plants and wind farms among others, distribution or transmission grids of large electric networks and entire micro-grids. The elements that support grid integration are focused on data acquisition, monitoring and control of all involved elements. This can be done by means of metering units and SCADA systems (Supervisory Control and Data Acquisition), overall system level control to improve energy dispatch of one or more applications, and possible operational optimization to maximize revenue streams and enhance market participation.

2.3. Li-ion BESS applications

Battery energy storage systems can cover the full range of the grid layout from low voltage (LV) up to high voltage (HV) including off-grid microgrids [35]. As for the purpose of the present paper, only large-scale Li-ion BESS applications are considered - the indicative minimum size is set at 50 kW storage systems. Hence, everything below that number is treated as residential storage and falls out of the scope of the review.

The possible applications of Li-ion BESS can be subdivided in three main groups: front-of-the-meter, behind-the-meter and microgrids. FTM is by far the category with most potential use-cases, including all grid services, wholesale market participation, large-scale renewable integration and support on transmission systems as well as distribution systems. Furthermore, large-scale BESS are most likely to play a relevant role within these applications. Next, BTM use-cases are centered on smaller batteries for a commercial & industrial (C&I) usage, which can be up-scaled by means of aggregation. Lastly, microgrids can also play a very relevant role, both in remote off-grid locations that rely on renewable resources as well as grid-connected systems that require backup solutions. See the detailed list of applications for each category in Table 2 [37].

Even though there are many potential applications, it is important to highlight that not all of them are economically feasible at this moment in time. Depending on each use-case, the value that distinct applications can provide varies significantly between each other [38]. Because of this, the present feasibility of large-scale Li-ion BESS projects cannot be related to all listed applications, and does often strongly rely on the combination of several of them. This can pose major challenges for the implementation of energy storage projects: unclear compensation schemes, operating models and ownership [39].

3. Li-ion BESS market overview

The large-scale Li-ion BESS market within the EMEA region is growing at a very fast pace, surpassing the number of installed MWh on a yearly basis. Overall, Li-ion storage solutions still represent a rather small share in comparison with pumped hydro energy storage (PHES) systems which have been present for many years, especially performing time arbitrage, forecast error correction and frequency control [1]. Nevertheless, the rate at which Li-ion based technologies are emerging in recent years is outstanding. The technical advantage of Li-ion BESS, constant decrease in price, operational flexibility and a big range of

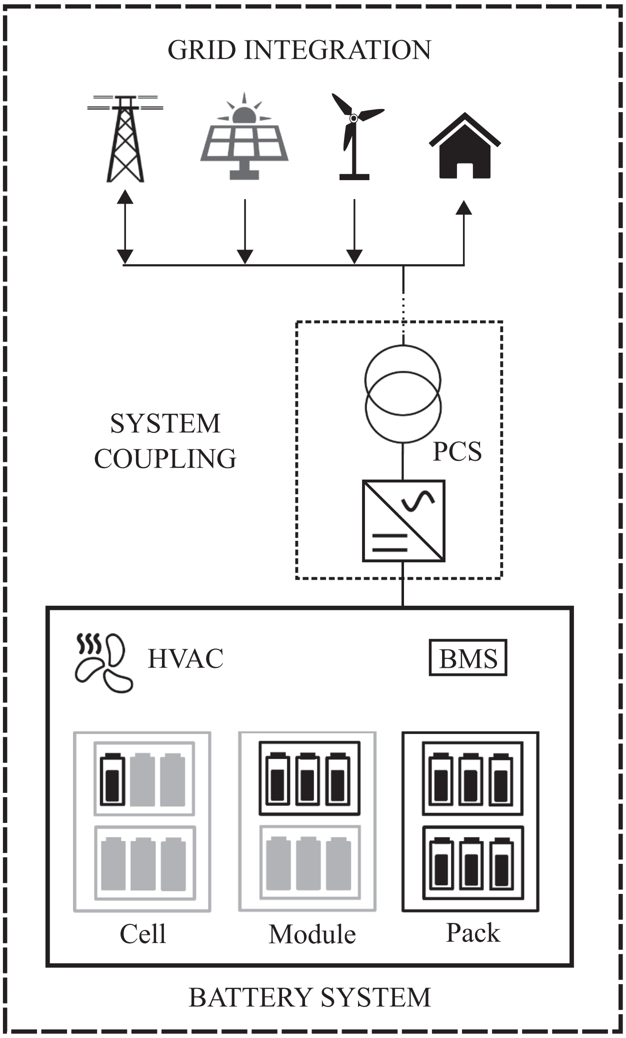


Fig. 1. Illustrative layout of a Li-ion stationary storage system interacting with loads, renewable energy sources, and/or the electric network.

Table 2
Technically feasible applications of large-scale Li-ion BESS connected to any level of the electric network or to isolated microgrids.

FTM	Grid Services	Balancing Mechanism (Ancillary Services)	Enhanced Frequency Response (EFR) – only in the UK Firm Frequency Response (FFR) –only in the UK Frequency Containment Reserve (FCR) Automatic Frequency Restoration Reserve (aFRR) Manual Frequency Restoration Reserve (mFRR) Replacement Reserves (RR)
		Passive Balancing	Imbalance Netting
		Power Quality	Voltage Support
		Black Start	
	Wholesale Market	Market Arbitrage	Day-ahead Market Intraday Market
	Renewables Integration	Time Arbitrage Forecast Error Correction Ramp Control	
	Transmission System	Peak Generation Replacement	Congestion Relief
	Distribution System	Resource Adequacy	Grid Stability Upgrade Deferral EV Charging Support
BTM	Commercial & Industrial	Increase PV Self-Consumption Tariff Optimization Backup Power UPS	Time Arbitrage Ramp Control Peak Power Reduction Power Outages Power Quality
	Aggregation	Virtual Power Plant	Grid Services Wholesale Markets Demand Response
Microgrid	Off-grid	Diesel Abatement LCOE Optimization Increase in Renewables Share	
	Grid-connected	Grid Backup	

potential applications can be very attractive. However, this is not applicable to every mentioned use-case and all regions. Present economic feasibility and project implementation are highly focused on a limited number of combined use-cases and specific conditions in certain regions and/or countries.

3.1. *Existing use-cases*

Li-ion BESS do undoubtedly present a vast number of potential applications where they can be beneficial in terms of overall value. Nevertheless, without economic feasibility, the implementation of BESS is rather unlikely with the exception of some singular cases. Currently, there is a limited number of use-cases that are not only favorable from a technical perspective but also present a profitable business case. This is because of the cost of Li-ion technologies - even though Li-ion batteries are facing constant price decrease, overall they are still an expensive technology. Furthermore, almost all economically viable projects are based on the combination of several applications that create diversified revenue streams.

Until now, the main implemented use-cases of large-scale Li-ion BESS in the EMEA region are the following:

- **1 - FTM Grid services** - Primary reserve (FFR/FCR) co-optimized with imbalance netting, potentially improved with capacity market revenues.
- **2 - FTM Renewables integration** - Time arbitrage, forecast correction and ramping in combination with possible grid services in remote and/or isolated locations.
- **3 - BTM Commercial & industrial** - Peak demand reduction and self-consumption in combination with possible grid services through aggregation.
- **4 - Off-grid microgrids** - Diesel abatement in remote and/or completely isolated locations.

Note that the viability of the aforementioned use-cases is completely dependent on the specific energy market condition and location.

3.2. *Geographical market share*

The presence of the main existing Li-ion BESS use-cases varies significantly across the EMEA region. This is reflected on having general regional tendencies towards specific applications. Moreover, not all countries and/or areas of each zone have ongoing or planned storage systems.

The main current trends are showcased in Fig. 2, where it is possible to distinguish between Europe (except the Iberian Peninsula, France and Greece), the Middle East and North Africa (MENA), and Sub-Saharan Africa. Europe has the most developed energy markets, which include well-defined balancing markets and can present favorable traits for C&I applications. The MENA region, similar to the Iberian Peninsula and France (mainly because of its islands [40]), encompasses many

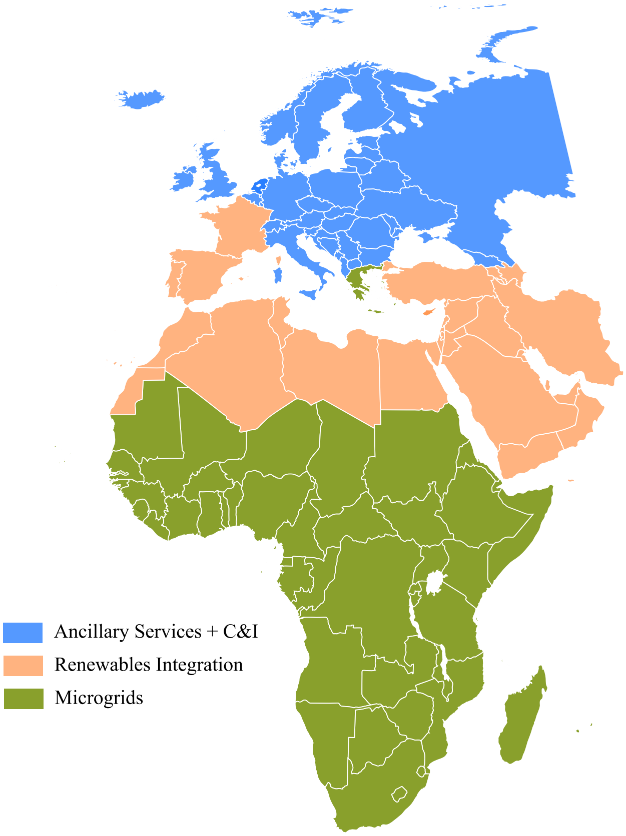


Fig. 2. General Li-ion BESS market overview of the EMEA region: main existing (or potential) use-cases.

remote locations that face expensive and sometimes complex energy supply, which in combination with very auspicious environmental conditions - especially when considering large-scale PV plants, is pushing the usage of batteries for renewable energy integration. Lastly, the less developed grid infrastructure in Sub-Saharan Africa, in addition to the vast amount of remote locations with no electricity network access, opens a promising opportunity for off-grid microgrids. This is also applicable in the specific case of Greek islands, which are to a large extent isolated from the continental grid.

Regional conditions have a different impact on Li-ion BESS implementations, wherein Europe is by far the most diversified and complex market in terms of present battery use-cases. To get a better understanding of existing projects as well as potential implementations, each region is reviewed in more detail next.

3.2.1. Europe

During the last decades, electricity markets have been opening up creating opportunities for the participation of BESS, especially when considering primary frequency regulation within ancillary services. Furthermore, high prices and/or penalties for peak demand periods, low PV costs and potential aggregation programs are raising the interest in C&I applications. However, the market layout as well as regulation frameworks vary with the country, which is why the presence of Li-ion battery projects is far from being homogeneous across Europe. The present market outlook in Europe is depicted in Fig. 3 according to information from [9], showing leading markets, existing implementations and known potential opportunities.

The UK and Germany are undoubtedly the leading countries for large-scale Li-ion BESS implementation for both ancillary services and C&I use-cases, not only in terms of installed systems but also presenting the largest energy storage units in Europe as listed in Table 3 [24]. The UK is the first European country that has opened a fast frequency response market as part of its grid services (EFR - enhanced frequency response) in order to mitigate constant frequency deviations because of being disconnected from the European continental electricity network. This proves to be very favorable for BESS since EFR requires asset activation within 1 s. Therefore, more than 200 MW of equivalent battery systems have been awarded in tenders for EFR in 2018. Furthermore, the primary frequency regulation service (FFR - firm frequency response) also requires a faster activation time than the rest of Europe (10 s vs. 30 s). Until very recently, the UK also featured a capacity market with long-term contracts, where more than 500 MW of equivalent BESS have been awarded contracts starting in 2020 according to Clean Horizon [41]. In terms of C&I use-cases for batteries, the UK has very favorable conditions because of sorely high tariffs on peak demand periods based on triad mechanisms. On the other hand, Germany has a well-functioning market for primary frequency regulation, especially with the open cooperation with neighboring countries (France, Austria, Switzerland, Belgium and the Netherlands), which has been pushing the implementation of more than 150 MW of equivalent storage systems during the last three years [41].

The third most relevant European market is France, which focuses on renewable energy integration. This is because France has numerous isolated islands and remote locations (mostly former colonies) where conventional energy resources based on fossil fuels can be very expensive. Therefore, the integration of renewable energy enhanced by BESS can have a very positive environmental impact and reduce the present levelized cost of electricity (LCOE) [42]. Until now there have been several awarded tenders for islands summing up more than 60 MW of storage implementation, including Corsica, Guadeloupe, Guyana, La Reunion, Martinique and Mayotte [43]. Note that these also include overseas regions, which are administrated by the French government.

There are several other countries and regions in Europe which also present existing and/or potential implementations of Li-ion storage solutions. Both Belgium and Italy have large-scale BESS with the aim to provide primary frequency regulation. Examples of these are the 18 MW Terhills project in Belgium [44] and the battery systems implemented in the south of Italy including the islands of Sardinia and Sicily summing up almost 20 MW [10]. Besides, there are several emerging markets with potential Li-ion BESS implementation due to recent initiatives or energy market changes. Examples of such are the high imbalance prices in the Netherlands, the capacity market opening in Poland, promising ancillary services in Finland, island microgrid initiatives in Greece [45] and the Sincrogrid project in Slovenia/Croatia [46].

3.2.2. MENA

The Middle East and North Africa is the region with the least ongoing Li-ion BESS projects in comparison to other areas within EMEA. Some of the reasons for the lack of present projects are monopolized energy markets, very little investments and political as well as economic instability [47]. However, MENA does show a very significant potential for large-scale renewable energy integration (it accounts for 45% of the worldwide renewable energy potential [48]) which has been kicked-off with several PV power plant projects. An example of this are the United Arab Emirates (UAE) and Saudi Arabia that plan to increase their share of renewable resources to a large extent [49]. One of the leading countries for Li-ion storage implementations is Jordan, with an ongoing 12 MWh Li-ion battery project in the mid-east region of the country, as well as a planned 30 MW BESS by the Ministry of Energy through a tender process [50].

3.2.3. Sub-Saharan Africa

The African continent, especially the Sub-Saharan region, has a favorable potential for the implementation of isolated microgrids. The two main reasons are that many areas do not have an extensive

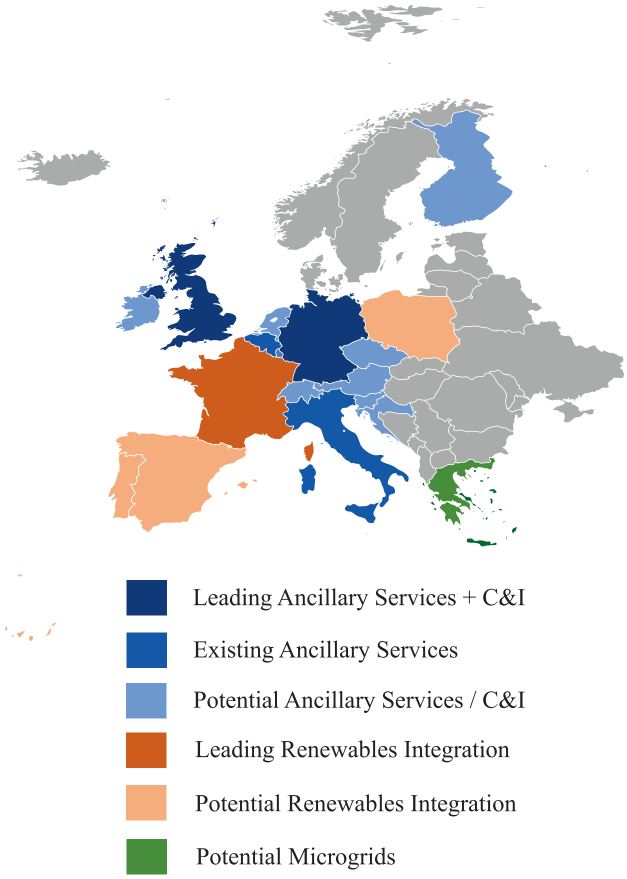


Fig. 3. Li-ion BESS market overview of Europe: main existing (or potential) use-cases per country, given concrete market regulations.

Table 3
Largest commissioned Li-ion BESS in Europe by 2018.

Rank	Project Name	Power (MW)	Energy (MWh)	Location	Main Application
1	Roosecote	50	50	UK	Frequency reg.
2	Jardelund	48	50	Germany	Peak replacement
3	Glassenbury	40	27.3	UK	Frequency reg.
4	Port of Tyne	35	n/a	UK	Frequency reg.
5	Tynemouth	25	12.5	UK	Frequency reg.
6	Pen y Cymoedd	22	16.5	UK	Frequency reg.
7	Broxburn	20	n/a	UK	Frequency reg.
8	Lunen	15	22.5	Germany	Frequency reg.
9	Walsum	15	22.5	Germany	Frequency reg.
10	Bexbach	15	22.5	Germany	Frequency reg.

electricity network infrastructure, and on top of that the existence of a large amount of remote locations. This results in having many hospitals, airports, factories, mines, hotels, lodges, public spaces and entire islands that are either completely dependent on diesel generators or have no electricity access whatsoever. Having this in mind, microgrids are not a real replacement for developed nation-wide electric grids, however, they can be very beneficial under certain circumstances. For this reason, the implementation of microgrids has been undergoing a big growth - the amount of people served by energy from microgrids on a global scale has increased by a factor of ten during the last decade [51]. This has resulted in the implementation of many microgrid projects including PV, storage units and diesel generators scattered across the African continent. Even though the size of this type of BESS is rather small in comparison to large-scale systems dedicated to grid services or renewables integration, the number of small projects that include Li-ion batteries tends to be higher than FTM grid-connected implementations, and usually have clear economic viability. Furthermore, according to Navigant Consulting, the currently installed microgrid capacity in Africa and the Middle East is going to increase by 500% in the following 10 years [52]. Up till now, there have been numerous microgrid projects in Botswana, Cape Verde, Chad, Equatorial Guinea, Kenya, Mauritania, Namibia, Nigeria, Seychelles, South Africa, and many more [53].

4. BESS use-case analysis

The implementation of large-scale Li-ion batteries is highly dependent on several factors related to energy markets, geography and specific needs in combination with rather complex revenue schemes. As mentioned in previous sections, there are only a few and very specific BESS use-cases that are being executed based on their potential profitability and are directly linked to specific geographies. Now, the implementation of these Li-ion BESS projects is correlated with specific requirements that enable a viable business case. In this section, each of the four present use-cases is going to be analyzed in order to identify and discuss the drivers that are defining the pursuance of present projects. However, before focusing on each use-case, both the cost structure as well as revenues in terms of added value will be determined in order to obtain a better understanding of the viability of the use-cases.

4.1. Levelized cost of storage

The levelized cost of storage (LCOS), similarly to the LCOE, is an indicator that quantifies the cost of energy storage systems, which can be done in relation to their dispatchable energy in MWh, or with respect to the available power in kW-year. This normalization provides a robust indicator of the existing costs per produced energy over the lifetime of the asset, or yearly available power, that can be used to compare different technologies and simplify the evaluation of economic feasibility. Before determining the LCOS computation, it is important to understand which cost components are relevant for large-scale Li-ion BESS (see Fig. 4).

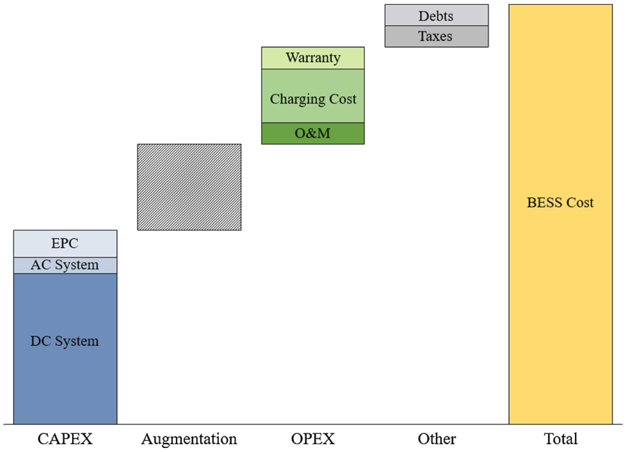


Fig. 4. Illustrative cost of Li-ion BESS projects including: system, augmentation, operational, and investment expenditures.

The capital costs of Li-ion BESS include the battery itself and the EPC process. The hardware of the battery can be subdivided in the DC system (cells, modules, packs, DC converters, BMS, cabling, etc.) and the AC system (HVAC, inverter, transformer, cabling, etc.). The capital expenditures (CAPEX) for large-scale Li-ion batteries corresponding to the DC system, based on known data and estimations distinct research studies and consultant reports ([12,41]), have been declining significantly during recent years. Currently, these costs are close to 300 €/kWh, with expectations to further decrease reaching 250 €/kWh in 2020. The trend of Li-ion BESS cost is depicted in Fig. 5, and compared to the gradual increase of global stationary storage deployments [54].

Next, because of the nature of electrochemical batteries, augmentation of the system also needs to be included in the overall cost. BESS are subject to charge and discharge losses regarding round-trip efficiency as well as gradual degradation over time due to their usage in terms of cycling, which could cause a disruption in the required employment for a particular use-case. Therefore, augmentation refers to the necessary expenditures to maintain a specific amount of usable energy over the lifetime of the system, either doing initial oversizing or restacking modular components. The operational costs of battery systems cover operation and maintenance, charging of the storage system (accounting for losses cause by overall efficiency) and extended warranty. Lastly, there are also additional costs that are relevant such as taxes, especially when considering grid connection expenses, and possible debts due to initial investments.

Unlike the LCOE, there is no standardized definition of the LCOS due to the nature of energy storage systems - the fuel costs are

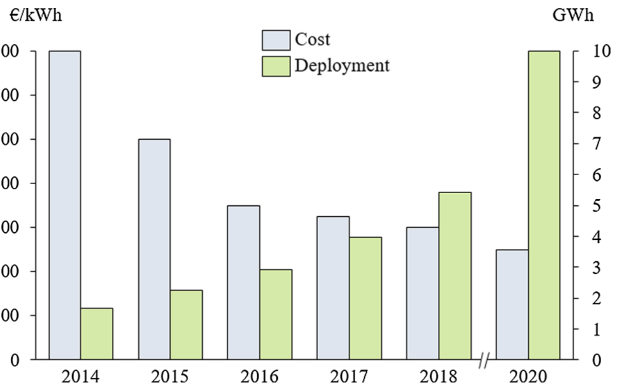


Fig. 5. Indicative trend and future projection of global Li-ion BESS CAPEX (DC-system) and total system deployment.

expressed as charging costs, which are highly dependent on the considered energy market and use-case. Furthermore, it is possible to benchmark LCOS with several indicators: required discharge price (minimum discharge remuneration to cover all costs), required price spread (minimum difference between charging and discharging price to cover all costs) or required operational profit (minimum required profit to cover all costs without accounting for energy losses) [55]. For the purpose of the present analysis, the LCOS that is used as a price indicator has been defined in terms of energy using (1).

$$LCOS = \frac{\sum_t (CAP_t + Aug_t + OP_t + Tax_t)\cdot(1+i)^{-t}}{\sum_t E_t\cdot(1+i)^{-t}}[€/MWh] \tag{1}$$

Wherein the levelized cost of storage is appraised in €/MWh. All related costs follow the same structure as indicated in Fig. 4, being CAP_t *[€]* the capital expenditures in year *t*, Aug_t *[€]* the augmentation costs in year *t*, OP_t *[€]* the operational expenditures in year *t* and Tax_t *[€]* the additional costs in terms of taxes and debts in year *t*. The annual dispatched energy by the battery system is depicted as E_t *[MWh]*, and *i* represents the discount factor. Aside, the LCOS based on power can be determined with a very similar formulation as defined by (2).

$$LCOS = \frac{\sum_t (CAP_t + Aug_t + OP_t + Tax_t)\cdot(1+i)^{-t}}{P\cdot T}[€/\text{kW} - \text{year}] \tag{2}$$

Here the BESS cost is the same as in (1), but instead of accounting for the total dispatched energy, the computations are based on annual available power in *kW*. Note that the relation between power and energy is defined by the C_{rate} of the battery (rate at which the battery is discharged in relation to its maximum capacity), and can differ for distinct applications. *P [kW]* designates the available power, and *T* the total number of years considered in the LCOS evaluation as the sum of all individual *t*.

In accordance with the formulation of (1) and (2), it is very difficult to recreate indicative LCOS prices that are illustrative for all Li-ion BESS use-cases. The LCOS is completely dependent on project-specific circumstances based on the system typology, manufacturer, energy market, project layout, involved stakeholders and location. Nevertheless, since the purpose of the analysis is to give a qualitative overview for a better understanding of present large-scale Li-ion battery implementations, it is possible to define LCOS estimates based on existing projects. More detailed cost-benefit evaluations of BESS sizing for distinct applications can be found in [35]. In accordance with the established LCOS from Lazard [17], indicative LCOS prices for 2018 have been approximated as depicted in Table 4, taking into consideration the average battery costs of existing projects and a discount factor of 8%. Note that the LCOS for grid services has not been taken from Lazard, but was extrapolated from known values based on the required battery C_{rate} for the application in most European markets.

The levelized cost of storage is expected to be significantly higher in BTM applications in comparison to FTM due to the smaller unit size which increases the normalized system cost. Micrograms also reflect a slightly increased LCOS because of higher system complexity translated in larger CAPEX and OPEX. Lastly, it is important to take into account that the relation between LCOS based on energy and power is highly dependent on the battery C_{rate}. Because of this, the LCOS related to power is expected to be much lower for grid service applications than for renewables integration, since primary frequency regulation usually requires 1C systems (1 MW/ 1 MWh) [41] while time arbitrage for integrating RES is rather based on C/4 configurations (1 MW/ 4 MWh) [56].

4.2. Revenue streams

The revenue streams of existing Li-ion BESS in the EMEA region, as already mentioned in previous sections, can be rather complex depending on multiple income sources. Furthermore, these sources are often very specific to where BESS can provide value within the energy system. For instance, wholesale market participation on predicted day-ahead auctions as a single source of revenues, similar to the use-case of the majority of conventional energy generators, could never work for large-scale Li-ion batteries. Taking into account the estimated LCOS for FTM applications of 235 €/MWh, it is not possible to create a profitable business case with average day-ahead energy prices ranging from 30 €/MWh - 80 €/MWh in Europe [57]. This is because almost all types of energy generators have a lower cost than Li-ion batteries, whose technological advantages do not present any value within the use-case. On the contrary, this would be quite different in applications that for instance require unpredictable activation with a fast response from the involved assets.

For all use-cases, it is very important to understand how the added value of Li-ion battery systems is monetized. Within any liberalized market, the most cost-effective technologies that are capable of providing a specific service, are the ones driving market prices or remunerations. Note that this might also happen in some monopolized markets. Hence, from a technological point of view, there are many areas where Li-ion BESS are advantageous in comparison to other technologies. However, if these technological benefits are not regulated within any specific environment or market, the added value cannot be monetized. Within FTM and BTM applications this is usually correlated with the market structure and applicable policy framework, whilst in the case of microgrids, it is more governmental and geography driven. Since large-scale Li-ion batteries used for grid applications are rather new, there are not many use-cases yet where their advantages get remunerated. Such an example is the enhanced frequency response service in the UK which requires an activation speed that most conventional generators are not able to achieve. Besides, special incentives and/or penalties for peak demand charges that can only be covered by shifting energy produced from PV panels in C&I use-cases favors the nature of any storage system.

The low number of applications that monetize the advantages of Li-ion batteries makes economically viable business cases difficult. Nonetheless, the operational flexibility of electrochemical energy storage systems allows the participation in several applications, either simultaneously in time or co-optimized. This trait has expanded the present implementation of battery projects improving the number of feasible use-cases - having several income sources, but also complicating the overall revenue scheme. Furthermore, these type of projects are to a large extent not only based on known revenues, but also on potential or speculated income as well as non-monetized value. Based on this, a typical revenue scheme for a Li-ion BESS project can be illustrated in Fig. 6.

Currently, battery projects are mostly based on two, or even more, known revenue streams, which all together are added up to construct a profitable business case. However, in some cases it is the potential revenues or the non-monetized added value that can be the decisive driver to overcome the existing LCOS. The distinct quantitative and qualitative revenue streams are defined below.

- *Existing revenues* - Revenues which are either known before the realization of the project or can be accurately estimated. Existing revenues can either be based on awarded and/or likely long-term contracts, expected remuneration from present market status, or

Table 4
Estimated LCOS per use-case of Li-ion batteries in 2018.

	Levelized Cost of Storage (LCOS)	
FTM - Grid services	235 €/MWh	83 €/kW-year
FTM - Renewables integration	235 €/MWh	330 €/kW-year
BTM - Commercial & industrial	750 €/MWh	375 €/kW-year
Microgrids	305 €/MWh	850 €/kW-year

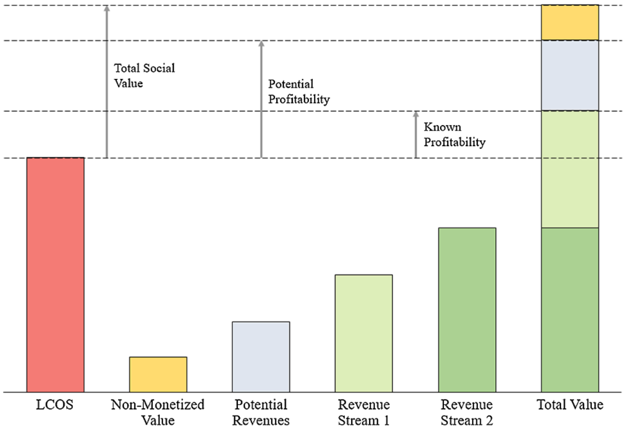


Fig. 6. Illustrative revenue streams of Li-ion BESS resulting from application stacking.

possible savings when considering peak demand reduction and fuel curtailment.

- *Potential revenues* - Potential revenues are those which are based on speculation about the future evolution of market prices and/or policy changes. These revenues cannot be quantified at this moment in time, but they might suppose a significant revenue augmentation in the future. Since Li-ion battery projects usually have an expected life-time ranging between 10 and 20 years, potential revenues can play a very significant role. However, they always include possible uncertainty, which is why they require a thorough risk assessment.
- *Non-monetized value* - Besides monetized revenues, added social, environmental or technological value can also be a driver for the implementation of Li-ion systems. This can happen when there is a specific need which is more important than actual economic profitability. Examples of these are the pursuance of sustainability towards low carbon emission, either personal or governmental, as well as required energy supply in remote locations that have neither access to electricity nor viable diesel supply.

4.3. Business cases

The present implementation of large-scale Li-ion BESS within the EMEA region is portrayed by four main use-cases that have fostered the realization of projects. In this section, each use-case is analyzed in order to get a better understanding of present viability while evaluating the associated requirements for the business case to work, the present and future potential of the involved storage applications, the overall risk and the key decision drivers that push the implementation of Li-ion batteries within the case. Note that the indicative results from each analysis are subject to the generalized LCOS assumptions described in Section 4.1; therefore, given project-specific BESS sizing and costs, the outcomes are likely to change.

CASE 1 - FTM Grid services

Use-case: Primary reserve (FFR/FCR) co-optimized with imbalance netting, potentially improved with capacity market revenues.

This use-case is based on the combination of primary frequency regulation, passive balancing (or intraday market participation) and potential revenues from long-term capacity market contracts. The main focus within this type of projects is usually the participation in FCR or FRR markets, while extending the revenues through smart state of charge management, and capacity market contracts when available. However, future market trends are pointing towards higher energy-based balancing markets. The main requirements, potential risks and key drivers of the use-case are depicted in Fig. 7.

In order to make this use-case viable, the most important requirement is to have a liberalized ancillary services market which allows the participation of BESS in primary frequency regulation. There might be some exceptions where monopolized markets owned by governments can also consider battery systems for this purpose, but so far it has not been the case. Moreover, the liberalized market also needs a beneficial regulatory framework (defined requirements for assets) in order to create added value for Li-ion BESS. This can be translated in fast response requirements (e.g. <10 s for FFR in the UK [58], <30 s for FCR in central Europe [59]), short deployment duration requirement for up and down frequency regulation (e.g. 30 min in France, 60 min in Germany [41]) and short deployment windows (e.g. expected 4 h delivery periods in central Europe instead of present weekly format [60]). Within all situations where a more flexible balancing market structure is present, BESS have accentuated advantages. First, for shorter demanded reaction time, batteries are more beneficial due to their very fast response. Second, for the shorter required duration of primary frequency regulation, batteries can be sized smaller (same nominal power with less available energy) while obtaining the same revenues. Last, for shorter delivery windows, BESS present high flexibility in terms of market participation, allowing the engagement in distinct deployment periods and/or markets. Furthermore, compensation schemes can also have a noticeable impact on the present income, such as the difference between paid-as-bid and paid-as-clear [61].

The remuneration of primary frequency regulation is based on reserved capacity during a specific time (deployment window) where the asset has to be available to correct fast frequency deviations when requested. Under the condition that awarded auction prices for primary frequency regulation are high, the use-case for Li-ion batteries can be very profitable. During the recent years, market prices for FFR in the UK and FCR in Germany have reached values close to 20 €/kW/hour, which has pushed many Li-ion BESS implementations because of high remunerations and advantages of battery storage technologies. An illustration of the possible revenues based on the market price can be seen in Fig. 8, which assumes an availability rate of 90%. Note that these results are qualitative and do not represent precise data since revenues are dependent on actual market participation and LCOS on project-specific costs.

As it can be observed, the use-case for primary frequency regulation, taking into account FCR/FFR prices close to 20 €/kW/h, is indeed very profitable. However, there is also a high associated risk. Initially, when BESS did not represent a big share within frequency regulation markets,

Requirements

- Open market for ancillary services
- Beneficial primary frequency regulation
  - Fast required response
  - Short required duration
  - Short deployment window
- High remuneration for FCR/FFR
- Imbalance market volatility

Potential

- Monetized technological advantage (speed)
- Imbalance market volatility increase – DERs
- Additional capacity market revenues

Risk

- Limited market size
- Decreasing FCR/FFR remuneration
- Dependence on market regulations

Key drivers

- Known revenues
- Speculation

Fig. 7. FTM grid services - overview of the use-case.

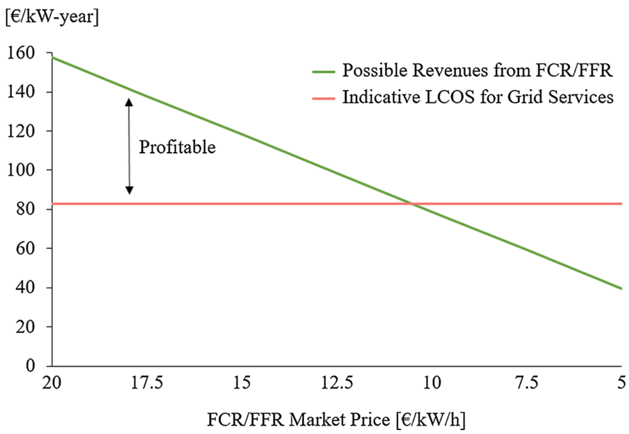


Fig. 8. Indicative revenues from FCR/FFR vs estimated LCOS of Li-ion BESS in the grid services use-case.

prices where driven by competing technologies (mostly gas turbines) which require a higher cost to provide the same service. Nevertheless, due to the law of competition within liberalized markets, the higher the integration of Li-ion BESS within ancillary services, remuneration prices for FCR and FFR are going to decrease approaching the cost for batteries to provide the service, causing market congestion [62]. Furthermore, ancillary service markets are very limited in size, preventing market growth. At this moment in time, prices have already decreased significantly in the main markets including the UK and Germany (up to 33% FCR price decrease in recent years [63,64]), being mostly around 10 €/kW/h - 15 €/kW/h. Therefore, the general market trend is pointing towards a significant price decrease within the next decade based on present tendencies. Nonetheless, the participation in primary frequency regulation also entails an important advantage - the actual activated power is on average significantly lower than the contracted capacity. Based on recent studies about FCR activation in Belgium, on average the capacity use stays below 10% of the reserved power during 90% of the time [65]. This activation factor is highly dependent on the frequency variations within the considered region, but under any circumstances below the contracted power capacity. This means that Li-ion BESS participating in primary frequency regulation have the potential to simultaneously participate in other applications (assuming sufficient energy availability).

The implementation of smart SoC strategies, either through passive imbalance netting or wholesale intraday market participation, can provide additional revenues within the present use-case. For all applications, the main challenge is unpredictability (short time periods where large price spreads can happen) as well as required activation speed, which can be the time between the gate closure and delivery period in intraday markets (lead time down to 5 minutes [66] for assets without TSO notification requirement) or instantaneous passive imbalance netting. According to this, BESS have significant advantages over distinct technologies in terms of response time and flexibility. Similar to day-ahead market participation, the aim here is to capture very high price spreads. However, because of the sometimes unpredictable net imbalance occurrences, imbalance prices (as well as intraday bids), can be very volatile. Taking into account the indicative Li-ion LCOS related to energy within Grid Services which is around 235 €/MWh (Table 4), any price spread above that can lead to very high revenues. The volatility of imbalance prices, similar to other energy market prices, is very dependent on the prevailing conditions among different countries. For instance, Belgium has been showing very accentuated imbalance prices every week during 2017 with prices above 300 €/MWh [67] - considering average power prices close to 35 €/MWh it makes a considerable profitable source of income. Furthermore, overall imbalance prices are expected to increase with the gradual integration of more distributed energy resources (DER), whereby the participation in balancing markets is becoming very relevant for the use-case. Lastly, additional revenues can be obtained from potential capacity markets, which designate long-term contracts with retribution based on standby capacity availability. This is one of the main reasons why the FTM Grid Services use-case had a noticeable impact in the UK.

The key implementation of Li-ion stationary storage projects in Grid Services, similar to most traditional FTM energy generators, is purely focused on profitable investments. Therefore, the main drivers that enable this use-case are based on known revenues and speculation on potential income. Furthermore, most investors focus on obtaining a very fast payback with high IRR (Internal Rate of Return), which conditions future market congestion - most projects rely on present primary frequency regulation. This can be very controversial since it will not allow a sustainable use-case in the near future [63,64]. As a result, many implemented BESS initially driven by FCR/FFR prices are already shifting to intraday market participation.

CASE 2 - FTM Renewables integration

Use-case: Time arbitrage, forecast error correction and ramping in combination with possible grid services in remote and/or isolated locations.

This use-case is based on the integration of large-scale renewable resources, such as PV plants or wind farms, in remote locations or islands. The purpose of implementing BESS is to improve the dispatchability of RES: shifting energy production to consumption (time arbitrage), forecast error correction to reduce disruptions due to unpredictable weather changes, and ramping to maintain constant power output during fast production fluctuations. Furthermore, in some cases, grid services can be stacked on top of the previous applications. The use-case overview of renewables integration is depicted in Fig. 9.

The existence of high renewable energy potential is indispensable for the implementation of viable Li-ion BESS for large-scale RES integration. Moreover, up to date, these applications are only profitable in remote or completely isolated locations which present elevated energy costs of traditional generators due to expensive fuel transportation. This is because time arbitrage based on continental wholesale markets alone cannot justify the expenses of a battery system (see Section 4.2.). In addition to that, the value of other applications such as forecast correction and ramping could not compensate for the big gap in required revenues for a profitable business case. An illustrative example of the dependence on energy costs is represented in Fig. 10, where the LCOE of coal plants [68] (often implemented on remote islands) is compared to the LCOS of Li-ion BESS. As it can be observed on the graph, the potential for savings from Li-ion BESS, even when

Requirements

- High renewable source potential
- Existing need for renewable sources
    - Environmental targets
    - Expensive conventional generators
- Required time arbitrage
- Governmental subsidies
- DC system coupling

Potential

- Very big future market
- Combination with Grid Services
- Sustainability value

Risk

- Dependence on Governmental subsidies

Key drivers

- Known revenues
- Non-Monetized value

Fig. 9. FTM renewables integration - overview of the use-case.

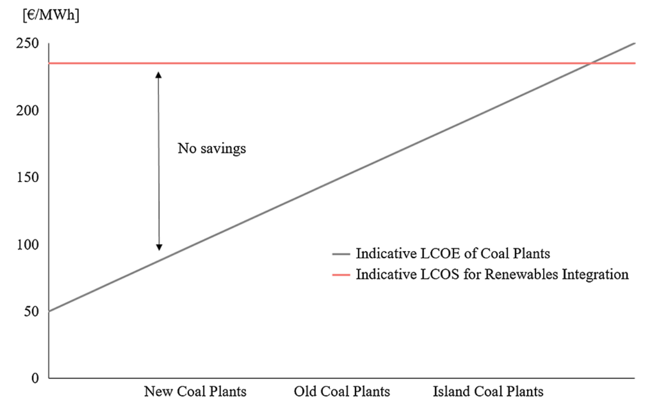


Fig. 10. Potential savings from BESS to enhance renewables integration in remote locations - coal plant LCOE vs. indicative LCOS of Li-ion batteries in FTM Renewables Integration.

accounting for remote locations such as islands, is very narrow. The overall cost of conventional power plants is significantly lower than the LCOS of Li-ion technologies. This is still the case for increased fuel prices due to additional transport and raw material expenditures. Note that this is only applicable for the LCOS of Li-ion BESS, the LCOE of renewable resources can be lower and more competitive with generators based on fossil-fuels in isolated locations.

The main driver for the implementation of BESS for renewables integration is therefore not based on direct savings, but on the benefits when combined with renewable resources as well as the added value of enhancing a low emission environment. Furthermore, the addition of grid services can significantly improve the overall retribution scheme. Under any circumstance, expensive conventional energy generators and inconvenient fuel transport are still required to justify project implementation with regards to overall feasibility. Hence, the key drivers can be defined as the known benefit of Li-ion BESS and the need for RES integration. BESS can facilitate RES to increase their load coverage time, strengthen against weather variability and maintain the power output during fast weather fluctuations. Besides, existing requirements on reducing CO_2 emissions enhance the need for RES, and consequently energy storage systems. This last point can be very relevant for governments, which are gradually creating roadmaps towards the elimination of fossil fuels.

During recent years, several public tenders have been opened for the implementation of BESS with the purpose of large-scale renewables integration on islands. Without any doubt, France has been leading on this with present projects on Corsica as well as several Caribbean islands within overseas territories such as Guadeloupe and Martinique. However, being dependent on governmental initiatives poses a significant risk for the use-case. Without economic support from public entities to pursue the goals of integrating RES, this type of projects is rather unlikely to happen. In practice, this can be defined as a barrier rather than a risk, since governmental support schemes for renewable resources are often inefficient or nonexistent [69]. However, this use-case does have a considerable potential for the future considering a large available market and existing value for sustainability. Once governmental subsidies are better defined and the LCOS decreases, large-scale renewables integration can have an important impact on Li-ion BESS implementation.

CASE 3 - BTM Commercial & industrial

Use-case: Peak demand reduction and self-consumption in combination with possible Grid Services through aggregation.

The C&I use-case is mainly based on providing peak power demand reduction to avoid power charges as well as elevated energy prices during high demand periods. Notwithstanding, it can also combine this with prolonged self-consumption based on renewable DER performing time arbitrage, and possibly participate in Grid Services through aggregation programs. The overall outlook of the use-case is summarized in Fig. 11.

Requirements

- High peak demand charges
- High daily load consumption spread
    - High load peaks
    - Short duration
- Required renewable source (PV, Wind, others)
- Governmental subsidies

Potential

- Big future market
- Possible asset aggregation
- Possible Power Purchase Agreement (PPA)

Risk

- Dependence on tariff structure
- Dependence on Governmental subsidies
- Dependence on policy regulations

Key drivers

- Known revenues
- Speculation
- Non-Monetized value

Fig. 11. BTM commercial & industrial - overview of the use-case.

The core requirements for the feasibility of the C&I use-case are a very volatile consumption profile as well as very high peak demand charges. The first point is very much related to the topology of Li-ion BESS, whose price is directly linked to the total size in terms of stored energy. Batteries can be very effective to lower short price peaks - reducing large peak power spreads within a short duration, which means that the required initial cost is relatively low in comparison to the given impact. On the contrary, slightly reducing prolonged high power periods which requires a very long duration battery would have the opposite effect. An illustrative example of the potential to reduce peak demand charges with BESS on volatile load curves is depicted in Fig. 12.

When considering the second point, peak power charges usually need to be enhanced through additional penalization or incentives in order to enable an economically viable battery implementation. A very simple example to showcase the need for additional revenues can be made comparing the LCOS of Li-ion batteries with the potential savings from energy tariff prices. Spain is taken as an example location since it has a notorious potential for small-scale PV implementation, with

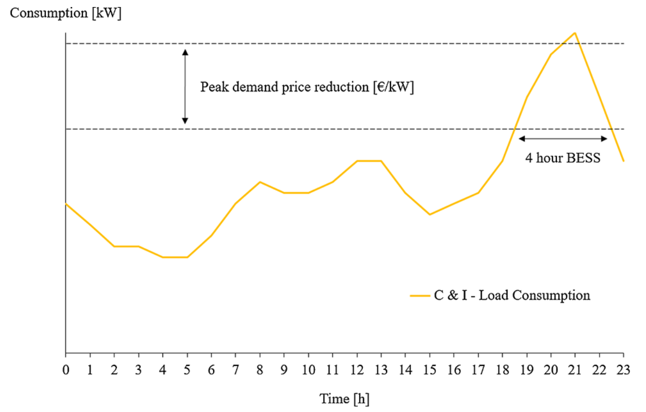


Fig. 12. Illustrative tariff savings reducing peak demand with BESS in C&I applications.

average demand tariff prices close to 8.5 €/kW-month [70] (similar to many countries in Europe). The estimated LCOS in terms of battery power for C&I applications is approximately 375 €/kW-year (Table 4). Taking into account a potential peak power reduction of 50%, and an average annual peak demand price of 102 €/kW-year (based on the 8.5 €/kW-month), the generated profit from a Li-ion BESS would be close to 51 €/kW-year, which is very far away from covering the given LCOS. Note that this is an illustrative example, as in real-life projects, the economic feasibility will be affected by further revenues from energy savings as well as potential grid services. However, very often additional regulations that penalize peak demand periods are needed to justify the use of batteries. A good example for this is the UK which has a very complex tariff structure, where several additional charges are applied to compensate for peak demand periods. These include charges for the usage of distribution (DUoS) and transmission networks (TNUoS) [71], charges for the utilization of distribution networks for generators (GDUoS) [72], extra charges during high demand time periods to recover costs of running the Capacity Market (CM Levy) [73], and peak power charges based on Triads (price charge in accordance with the three highest half-hour settlement periods with maximal system demand) [74].

C&I applications can be very beneficial for Li-ion BESS under the right circumstances, and even more when considering the possibility of Virtual Power Plants (VPP) operated through aggregation for market participation in ancillary services. However, there are also associated risks which cannot be neglected - dependence on tariff structures, governmental subsidies and policy regulations. There are no long-term contracts that ensure any given revenue or saving, meaning that the price retribution scheme from which battery systems can profit can disappear as fast as it was introduced in the first place. A representative example of this is the creation of the so-called ”sun tax” in Spain during October 2015, which instead of favoring small-scale PV systems for self-consumption purposes, charged them for making use of solar energy instead [75]. This change in regulation, that by now has already been abolished (October 2018), completely eradicated the possibility of having economically feasible C&I use-cases in one of Europe’s countries with the largest PV potential.

The key driver for the implementation of batteries in the C&I use-case is without a doubt the possible economic benefit in terms of tariff savings. Nevertheless, speculation on future price evolution and regulatory changes, as well as added non-monetized value from enhanced sustainability, do also account as decision drivers making it the most interdisciplinary case. All in all, this type of investments are based on profitable business cases in combination with added value rather than the fulfillment of any given need.

CASE 4 - Off-grid microgrids

Use-case: Diesel abatement in remote and/or completely isolated locations.

The off-grid microgrid use-case is based on the reduction of diesel utilization in remote places which require energy supply and are subject to very high diesel prices (often due to difficult transportation). The main traits of the use-case are listed in Fig. 13.

Isolated microgrids are the simplest use-case in terms of clear feasibility. It is applicable to any remote location that has the need for electrical energy consumption and currently depends on diesel generators or do not have any electrification yet. Based on the given diesel prices, it is possible to asses the profitability of Li-ion BESS in microgrids as a function of diesel cost savings. Fig. 14 showcases a comparison between energy generation costs of a diesel engine, assuming an overall efficiency of 35%, and the estimated LCOS of Li-ion batteries implemented in microgrids.

For any scenario where diesel prices are at least 1 €/L - 1.2 €/L, batteries are more than viable in order to reduce overall LCOE of microgrid systems based on PV (or other renewable source), storage and diesel generators. Note that the exact crossing between energy generation cost from gensets and LCOS is only indicative and can vary depending on project-specific conditions. Furthermore, the blended LCOE of PV and storage, which is significantly lower than the LCOS, can drive down the required diesel price for a viable business case. This results in a very good business case for isolated islands that tend to have diesel costs close to 1.5 €/L, obtaining a benefit of around 31%.

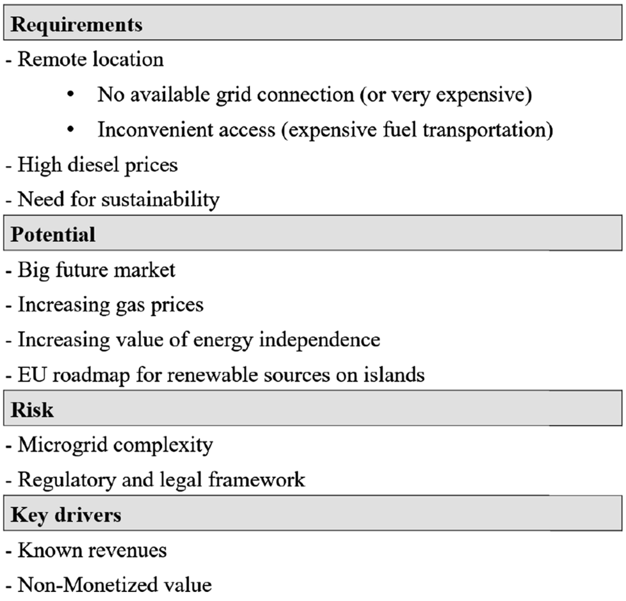
The present potential of microgrid implementation is very noticeable. First, there are many remote locations within the EMEA region, especially in Africa as well as Mediterranean islands, that could profit from microgrids. Second, gas prices tend to increase based on general market prospective, which enhances the value of energy independence. Lastly, similar to large-scale renewable integration, there are several governmental roadmaps that aim towards energy independent islands based on clean renewable resources, creating numerous future opportunities.

The main source of risk for microgrids is their technical complexity, which is sometimes interpreted as immature technology, and prevents a larger number of implementations. Besides, regulatory frameworks are often not well defined since microgrids are rather new in several regions. Nevertheless, microgrids are slowly getting settled as the number of successful implementation increases lowering the mentioned risks.

The implementation of microgrids, and therefore possible usage of Li-ion batteries, is based on key drivers that differ considerably from investment-ruled projects (maximizing profit within short time) that often rely on speculation such as in the case of Grid Services and sometimes C&I cases. Off-grid microgrids are almost always installed out of an existing need in combination with a very well known business case. However, there can be exceptions where the value of clean energy generation surpasses a non-profitable business case, which can sometimes happen in private projects driven by environmental awareness.

5. Future Li-ion BESS Outlook

The future outlook of Li-Ion BESS implementation within the EMEA region is highly dependent on the impact of present use-cases, gradual technological development, constantly changing policy frameworks and energy market regulation. Therefore, in order to get a better foresight on possible future Li-ion BESS market trends, it is important to understand the factors that influence the realization of large-scale battery projects. These include the following: technological advancements in terms of expected Li-ion battery improvements, system cost reduction, development of competing technologies, changes in grid codes, energy market structure, governmental regulations, present investments in



Requirements

- Remote location
    - No available grid connection (or very expensive)
    - Inconvenient access (expensive fuel transportation)
- High diesel prices
- Need for sustainability

Potential

- Big future market
- Increasing gas prices
- Increasing value of energy independence
- EU roadmap for renewable sources on islands

Risk

- Microgrid complexity
- Regulatory and legal framework

Key drivers

- Known revenues
- Non-Monetized value

Fig. 13. Off-grid microgrids - overview of the use-case.

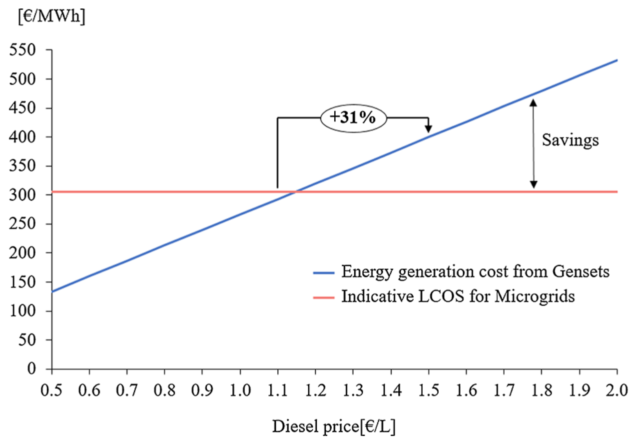


Fig. 14. Potential savings from diesel reduction based on fuel price - diesel generation cost vs indicative LCOS of Li-ion batteries in microgrids.

battery systems, increase of RES and DER (prosumers), and potential new use-cases.

5.1. Technology development

Large-scale Li-ion BESS systems are undergoing a very fast technological improvement due to a significant research push. This will lead towards increased system performance as well as continuous cost reduction (limited by raw material prices). Nonetheless, there are several other energy storage technologies which are also being developed at a fast pace and might be able to compete or even surpass Li-ion batteries for specific use-cases.

First, from a purely technical point of view, there are several expected developments in terms of new system layouts and material improvements on the cell chemistry level. According to the European Commission, targets for Li-ion batteries include the achievement of an energy density up to 350 Wh/kg and specific power of 5 kW/kg [39] within the next decade. This accounts for an improvement of approximately 50% with respect to present numbers. One way to influence specific energy and power is by developing further the Li-ion cell chemistry, even though that can only have a limited impact under present conditions. Li-ion cells have concrete energy and power boundaries based on their electrochemical properties, wherein existing values are not too far off from theoretical limits. Therefore, little margin for improvement is left on present used cell types - unless a complete different chemistry is considered. What can make a bigger impact is the design of new physical layouts in order to fit more cells in less space creating very compact BESS.

Future targets also aim to significantly increase potential life-cycles of Li-ion batteries, which is very important in stationary storage applications that require system durability of 15–20 years. Until now, LFP battery cells have a very promising potential to achieve higher cycling [76]. This is one of the reasons why LFP is gaining relevance within BESS manufacturers. Nonetheless, LFP cells have a lower specific energy (90 Wh/kg–140 Wh/kg) with respect to implemented Li-ion batteries based on Nickel Cobalt Aluminum (200 Wh/kg–250 Wh/kg) and Nickel Manganese Cobalt (140 Wh/kg–200 Wh/kg) [19].

Technological developments are not only reflected in terms of performance improvement, but will also lead to a constant decrease in system costs. These are highly correlated with scaling the production in an efficient manner and improving system design [77]. The present prices of Li-ion batteries have declined by nearly 40% based on known market data [41] during the last five years. Future expectations are following a similar path; Bloomberg estimates another 30% reduction by 2025 and 52% by 2030 [78].

The abundance of materials implemented in large-scale Li-ion BESS is a factor that noticeably influences the future technological development. The overall Li-ion battery market - accounting for all applications (not only stationary storage), has an annual growth of 26% [12], whilst raw materials to produce the cells are limited. Therefore, a possible lack of primary resources to manufacture different types of Li-ion cells is an existing risk. Unlike many beliefs that worldwide lithium production will soon run short with increasing market growth of Li-ion batteries, lithium is not a critical material at this point in time. Expectations are that lithium is going to be sufficient for the 21st century [79], even though it might be critical when looking at long-term predictions. Furthermore, many of the remaining materials implemented in Li-ion cells, such as Aluminum, Iron, Manganese, Nickel and Carbon, are not critical now and are not expected to be in the future. However, this is not true for cobalt, which does not present sufficient resources to face the growing market demand. Because of this, manufacturers of Li-ion batteries for stationary storage applications are slowly trying to reduce the dependence on cobalt, either decreasing shares of cobalt within NCA and NMC cell chemistry, or promoting the implementation of LFP cells. Besides, recycling is also going to play an important role in order to confront the lack of cobalt resources [19].

Lastly, the future development of Li-ion BESS is also dependent on the future improvements of competing energy storage technologies. So far, there are many different types of energy storage systems that are either implemented in real applications or are currently under development [80]. These can be classified in mechanical, electrical, electrochemical, chemical and thermal storage. Not all of them will compete to the same extent with Li-ion BESS because of very distinct technological advantages and applications in terms of available power, energy, lifetime and physical design. Examples of energy storage technologies that focus on distinct applications are thermal energy storage, which is most efficient when coupled to heat related power sources, or Pumped Hydro Energy Storage (PHES), that has a significant geographical impact. Out of all existing energy storage technologies, there are several which are either already competing, or might be a promising alternative for Li-ion batteries in the future. These are listed in Table 5, indicating their corresponding energy density, specific power, round-trip efficiency and expected lifetime [81].

At this moment in time, Li-ion batteries represent the best commercially available energy storage system in terms of trade-off between specific energy, power, efficiency and cycling. Even though many storage technologies have appealing characteristics, often surpassing Li-ion batteries (see Table 5), most of them are not commercialized under these specifications yet. This enables the usage of Li-ion technologies in many distinct applications, which as a consequence eases scaling up the production. However, other energy storage technologies are expected to catch up on this head start with future improvements. Supercapacitors and superconducting magnetic storage have potential for short duration use-cases, while flow batteries are promising for long duration applications. Note that these three technologies are considered within the

Table 5
Overview of distinct energy storage technologies: potential competitors for Li-ion BESS.

Technology	Energy density (Wh/kg)	Specific power (W/kg)	Efficiency (%)	Lifespan (Years)
Compressed Air	3.2–60	2.2–24	57–89	20–40
Flow Batteries	10–90	5–166	60–88	2–20
Flywheel	5–200	400–30000	70–96	15–20
Li-ion	30–300	8–2000	70–99	2–20
Lead Acid	10–50	25–415	63–90	3–20
Hydrogen	100–1500	2–150	10–85	1–10
Pumped Hydro	0.3–1.33	0.01–0.12	65–87	20–80
Sodium-Sulfur	100–240	15–260	65–92	5–20
Supercapacitor	1–85	1–100000	65–99	5–20
Superconductor	1–75	1–15000	80–99	20–30

same market niche of modular storage systems that have a low impact on geography or required physical space.

To conclude this section, it is relevant to mention second-life EV batteries, which are expected to influence future project deployments. So far, their presence in stationary storage implementations has been rather restricted, despite some pilot projects such as the 22 MW system installed at the Pen y Cymoedd onshore wind farm in the UK [82]. However, as the number of available second-life BESS increases, due to the present boom of EVs, it is likely that an increased proportion of reused batteries for grid applications will be observed in the future [83]. Nevertheless, given that the cell chemistry of EV batteries has been designed for mobility applications with limited cycling requirements in comparison to most stationary storage systems, second-life BESS are not well-suited for all possible use-cases as they might face severe energy degradation and therefore, limited lifespan [84]. Hence, depending on the considered application and location of the resources, it is important to assess the trade-off between reusing and recycling EV batteries.

5.2. *Grid code, energy market structure and governmental regulations*

The regulatory frameworks of applicable grid codes, energy markets and governmental regulations are substantial drivers within the future implementation of Li-ion BESS. Independently of technological improvements and cost reductions, energy storage system use-cases are always bound to existing grid codes (requirements for generators), volatile electricity prices dependent on market rules, and governmental subsidies and laws.

Grid connection codes are relevant tools in order to determine the requirements that any generator connected to the electric network needs to fulfill. As for now, with the exception of pumped hydro storage, energy storage systems have not been implicitly recognized in the Requirements for Generators (RfG) within the European Grid Code (commission regulation 2016/631) [85]. This has left space for some opportunities as well as many obstacles when it comes to product certification, having unclear applicable requirements. Notwithstanding, this will change in the near future - the working groups of the European Network of Transmission System Operators (ENTSO-E) are in the process of redefining the European Grid Code with initiatives from the European Association for Storage of Energy (EASE) [86]. Aside, several TSOs have already included energy storage systems under the same applicable RfG regulations as Power Park Modules (non-synchronous or power electronic connected generators) in their corresponding locations. This is an improvement in comparison to not having any applicable regulations. Some of the given terms are not coherent with the nature of energy storage technologies.

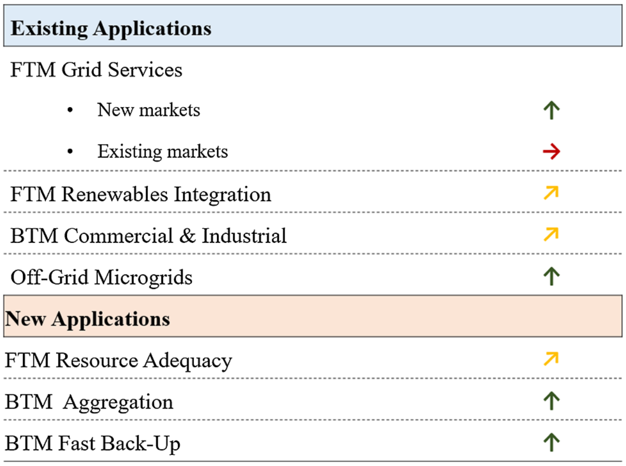
Energy market regulations determine the revenue structure from both wholesale and balancing markets, conditioning how the added value of BESS can be monetized. Therefore, changes in market network codes can influence the possible use-cases for Li-ion stationary storage systems significantly. This is applicable to the general market layout as well as specific points for energy storage. Some of the general rules that are critical for battery systems include market window closure, activation time, deployment periods and the possible creation of local markets. All in all, the more flexible the market is in terms of short-term decision making, fast activation and short deployment times, the more advantages of energy storage systems will be recognized. On the other hand, considering the specific market network code for energy storage, several changes are expected since a regulatory framework is not existent yet. The main points of discussion are currently focused on determining a proper definition of energy storage (including all technologies), clarity on market access rules, possible long-term contracts and the avoidance of double taxation [87]. Once these items are properly established, the conditions of market participation for energy storage systems are expected to improve.

Lastly, imposed regulations from national and regional governments also play a major role within the future implementation of Li-ion BESS. The main areas of interest where governments are involved include taxation of energy usage and system operation within BTM use-cases, and the provision of incentives for the enhanced introduction of renewable resources, both small and large-scale. The impact of taxation can be either positive or negative depending on the specific applicable rules, awarding the introduction of local generation or creating charges for the implementation of DER. The provision of subsidies for renewable energy integration does always have a positive effect on future BESS projects creating a larger number of opportunities. These are critical for the viability of many use-cases, and expected to slowly increase with governmental initiatives taking into account milestones of low carbon emission road maps [69].

5.3. *Future market trends*

The future evolution of Li-ion BESS within the EMEA region, besides being bound to upcoming technological and regulatory changes, is also affected by present project implementations and new arising opportunities. This is because existing projects can have an impact on possible market saturation. Furthermore, initiatives from entities that are involved or interested in stationary storage solutions (battery manufacturers, utilities, TSOs, DSOs, EPC contractors, investors and end-users) can accelerate the introduction of new applications. The overall market growth rate, according to present studies from Delta, is expected to be between 40% and 50% annually in Europe [10]. Meanwhile, both MENA and Sub-Saharan Africa are foreseen to follow up at a slower rate. Note that this increase is not equally distributed for all existing and new possible use-cases. Based on the present market status, foreseen technological developments, gradual cost reduction, regulatory changes and existing initiatives, an indicative trend of the future growth of Li-ion BESS use-cases is displayed in Fig. 15. Both existing applications as well as new potential use-cases are included.

The existing applications refer to the previously discussed use-cases from Section 4.3. Each of these is expected to have distinct long-term tendencies. FTM Grid Services are constrained by the limited market size and decreasing remuneration of primary frequency reserve. This is driven by the introduction of more energy storage systems that gradually lower existing prices which were initially determined by the operational costs of gas plants. Given that Li-ion batteries can be very beneficial within grid services, there will be many potential opportunities in new markets. However, existing markets such as the UK and Germany are expected to experience the effects of saturation in the near future. Under these circumstances, BESS that are (or will be) deployed in known markets are likely to shift their focus towards wholesale market participation - intraday and passive imbalance netting. This is



Existing Applications	
FTM Grid Services	
• New markets	↑
• Existing markets	→
FTM Renewables Integration	↗
BTM Commercial & Industrial	↗
Off-Grid Microgrids	↑
New Applications	
FTM Resource Adequacy	↗
BTM Aggregation	↑
BTM Fast Back-Up	↑

Fig. 15. Indicative long-term future evolution of Li-ion BESS use-case implementation within the EMEA region.

supported by the fact that wholesale market prices are estimated to increase significantly. According to the International Renewable Energy Agency [88], prices are going to double in comparison to present values [89].

Both FTM renewables integration and BTM commercial & industrial applications will likely increase their implementation rate at a slow path. Storage systems used to integrate renewable energy resources have a promising future, both in terms of environmental value and large potential market. However, many of these projects are tied to governmental support which does not always increase at a fast pace. From an end-user perspective, C&I applications are catching the interest of many entities that value the independence from elevated energy bills with volatile prices while enhancing sustainability. In particular, the implementation of power purchase agreements (PPAs) can improve the attractiveness of such projects. According to studies from Bloomberg, PPAs have increased by a factor of ten within the past five years in the EMEA region [90]. Nevertheless, the economic feasibility of this use-case is dependent on applicable tariffs, which can vary significantly over time, either enhancing the value of batteries or de-rating it.

Complete off-grid microgrids are expected to follow the current tendency of growing fast in the near and long-term future. The use-case has proven to be very effective to tackle high diesel prices in remote locations, and the number of existing and potential opportunities is very widespread. Furthermore, the very compressed and modular Li-ion batteries present a significant commercial advantage in front of any voluminous system [91].

Aside from the existing use-cases, there are several new applications which are expected to become more relevant within the near future. These include distribution grid resource adequacy, small scale BESS aggregation, and grid-connected microgrids for backup. Until now, none of them has proved consistency within the EMEA region due to high associated costs or complexity. Notwithstanding, both interest and demand are high, which is why they will presumably play an important role in the future Li-ion battery deployment.

Resource adequacy has always been of major technological interest. Both solving energy transmission congestion as well as grid stability problems, without modifying the network infrastructure nor increasing generation capability, can be very appealing. Nevertheless, this application is still far from being economically feasible due to cheaper solutions such as demand response and controlled power electronics in DER [92]. Furthermore, it is rather complex to quantify revenue streams when considering the nature of the application - avoiding possible costs from future demand increase. However, this might change with a fast increase in circulating EVs and installed DER. BESS can be a simple solution to perform peak shaving on large EV charging stations or avoid grid disturbances due to power injection from small-scale generators in highly populated areas. On top of that, other applications can easily be combined with resource adequacy having known and/or expected peak demand periods.

Aggregation programs are not only a promising idea, but many initiatives are already working on the creation of VPPs combining small battery sites. The benefit is based on the concept of grouping several small to medium-scale energy storage systems, through which new applications can be added on top of the BTM use-cases. These include most FTM applications: provide grid services, participate in wholesale markets and support resource adequacy [93]. The present analysis has only focused on large-scale Li-ion BESS implementation excluding residential units, however, these are going to play a major role in aggregation programs. An example of such is the aggregation project from the German battery company “Sonnen”, which has a network of 30,000 residential BESS in Europe. With this, they have the capability to create a VPP with a capacity up to 300 MWh. After contacting all German DSOs for approval, they are refining the plan to provide grid services [94].

Lastly, BTM back-up solutions are expected to grow at a fast pace within the future. The application is very case-dependent, whereas the economic business case is related to the leveraged value that electricity back-up can provide in specific locations. Examples of such are data centers, where each second of power loss supposes a significant cost, or hospitals which cannot tolerate power outages while treating patients. The aim of Li-ion BESS is to replace expensive diesel generators and old Uninterruptible Power Supply (UPS) systems to improve response time [95]. Until now, some barriers for the expansion of Li-ion BESS in this application within the EMEA region have been an immature market as well as complex certification requirements. However, this is highly likely to change in the near future with an increasing need for fast back-up solutions.

6. Conclusions

Li-ion battery energy storage systems (BESS) have become important assets within electric networks in Europe, the Middle East and Africa (EMEA) during recent years. Stationary storage systems based on Li-ion cells have significant technological advantages in comparison to present commercially available energy storage solutions, pushing towards a combination of high energy density and specific power. The advantages result in modular battery systems that occupy rather little space and are easy to implement. Taking this into account, the possibilities for battery applications are many from a technological point of view.

The real-life implemented use-cases of Li-ion BESS are rather little in comparison to all potential applications. This is because Li-ion based batteries are an expensive technology, which requires elevated income sources on top of added non-monetized value to justify their implementation. As for now, the main use-cases are focused on the combination of applications within four areas: front-of-the-meter (FTM) grid services, FTM renewables integration, behind-the-meter (BTM) commercial & industrial and off-grid microgrids. The deployment of energy storage systems for the use-cases is not homogeneous across the EMEA region, presenting different tendencies in Europe,the Middle East and North Africa (MENA), and Sub-Saharan Africa.

Each of the four use-cases does only work when specific requirements are met. These are related to market prices and regulations, applicable policies, governmental subsidies, cost of alternative technologies, location accessibility and environmental value. All in all, battery systems can be very beneficial, but it is important to understand which are the needed revenue streams that allow the economic feasibility of energy storage projects.

The future outlook of Li-ion BESS is promising, facing continuous growth in project implementations. Technology advances, cost reduction, policy changes and new opportunities will define the future development of stationary storage. Some of the present use-cases are likely to congest in the following years, while several new feasible applications will appear. At any rate, competing technologies are going to play a major role across distinct use-cases, narrowing the gap in technological advantages.

To conclude, Li-ion BESS are a very promising technology to enable a gradual shift towards decentralized power generation based on renewable resources. So far, their presence within the EMEA region is increasing at a fast pace. However, it is important to understand how different use-cases work and what is needed to create added value as well as an economic benefit. Under most circumstances, Li-ion battery projects are not economically feasible. Those that are, usually rely on complex revenue schemes in order to achieve financial viability. Nevertheless, the impact of Li-ion BESS is undoubtedly significant within the future evolution of electricity networks to accomplish a large share of clean energy generation.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

[1] Sandia National Laboratories, “Global Energy Storage Database”; 2019. [Online]. Available: <https://www.energystorageexchange.org/projects/data_visualization> [accessed: 2- Jan- 2019].

[2] Eurelectric - Union of the Electricity Industry, “High level questions to the Electricity Coordination Group on storage”; October 2018.

[3] Peker M, Selin Kocaman A, Kara BY. Benefits of transmission switching and energy storage in power systems with high renewable energy penetration. Appl Energy 2018;228:1182–97.

[4] Hill D, Mills-Price M. “2018 Battery Performance Scorecard”. DNV GL Energy; November 2018.

[5] Braeuer F, Rominger J, McKenna R, Fichtner W. Battery storage systems: an economic model-based analysis of parallel revenue streams and general implications for industry. Appl Energy 2019;239:1424–40.

[6] Pandzic H, Dvorkin Y, Carrion M. Investments in merchant energy storage: trading-off between energy and reserve markets. Appl Energy 2018;230:277–86.

[7] Conlon T, Waite M, Modi V. Assessing new transmission and energy storage in achieving increasing renewable generation targets in regional grid. Appl Energy 2019;250:1085–98.

[8] Hornsdale Power Reserve, “Overview”; 2017. [Online]. Available: <https://hornsdalepowerreserve.com.au/overview/> [accessed: 2- Jan- 2019].

[9] Geuss M. “Tesla strikes another mammoth energy storage deal in California”, arsTechnica; July 2018. Available: <https://arstechnica.com/information-technology/2018/07/california-utility-looks-to-add-gigawatt-hours-of-battery-storage-before-2020/> [accessed: 2- Jan- 2019].

[10] EASE - European Association for Storage of Energy, Delta Energy & Environment, “European Market Monitor on Energy Storage - Snapshot of the latest status and trends in Europe”, EMMES 2.0; June 2018.

[11] Solar Media. “Global Energy Storage Opportunity 2018. Special Report; 2018.

[12] Tsiropoulos I, Tarvydas D, Lebedeva N. “Li-ion batteries for mobility and stationary storage applications”. European Commission, JRC Science for policy report; 2018.

[13] Geth F, Brijs T, Kathan J, Driesen J, Belmans R. An overview of large-scale stationary electricity storage plants in Europe: current status and new developments. Renew Sustain Energy Rev 2015;52:1212–27.

[14] European Commission. “Future brief: towards the battery of the future”, Science for Environment Policy, vol. 20; September 2018.

[15] Sufyan M, Rahim NA, Aman MM, Tan CK, Raihan SRS. Sizing and applications of battery energy storage technologies in smart grid system: a review. J Renew Sustain Energy 2019;11.

[16] Dehghani-Sanij AR, Tharumalingam E, Dusseault MB, Fraser R. Study of energy storage systems and environmental challenges of batteries. Renew Sustain Energy Rev 2019;104:192–208.

[17] Lazard. “Lazard’s Levelized Cost of Storage Analysis - Version 3.0”; November 2017.

[18] Few S, Schmidt O, Gambhir A. Energy access through electricity storage: insights from technology providers and market enablers. Energy Sustain Develop 2019;48:1–10.

[19] Zubi G, Dufo-Lopez R, Carvalho M, Pasaogtu G. The lithium-ion battery: state of the art and future perspectives. Renew Sustain Energy Rev 2018;89:292–308.

[20] Li M, Lu J, Chen Z, Amine K. 30 Years of lithium-ion batteries. Adv Mater 2018;30(33).

[21] Klausen M. Market opportunities and regulatory framework conditions for stationary battery storage systems in Germany. Energy Proc 2017;135:272–82.

[22] Malhotra A, Battke B, Beuse M, Stephan A, Schmidt T. Use cases for stationary battery technologies: a review of the literature and existing projects. Renew Sustain Energy Rev 2016;56:705–21.

[23] Fleer J, Zurmuhlen S, Meyer J, Badeda J, Stenzel P, Hake J-F, et al. Techno-economic evaluation of battery energy storage systems on the primary control reserve market under consideration of price trends and bidding strategies. J Energy Storage 2018;17:345–56.

[24] Wingren L, Johnsson J. Battery Energy Storage Systems as an alternative to gas turbines for the fast active disturbance reserve M.S. thesis Sweden: Dept. of Energy Sciences, Lund University; 2018.

[25] Dusonchet L, Favuzza S, Massaro F, Telaretti E, Zizzo G. Technological and legislative status point of stationary energy storages in the EU. Renew Sustain Energy Rev 2019;101:158–67.

[26] Li X, Chalvatzis KJ, Stephanides P, Papapostolou C, Kondyli E, Kaldellis K, et al. Bringing innovation to market: business models for battery storage. Energy Proc 2019;159:327–32.

[27] Muller M. “Stationary Lithium-Ion Battery Energy Storage Systems A Multi-Purpose Technology”, Ph.D. dissertation, Department of Electrical and Computer Engineering, Technical University of Munich; June 2018.

[28] Braeuer F, Rominger J, McKenna R, Fichtner W. Battery storage systems: an economic model-based analysis of parallel revenue streams and general implications for industry. Appl Energy 2019;239:1424–40.

[29] Mir Mohammadi Kooshknow SAR, Davis CB. Business models design space for electricity storage systems: case study of the Netherlands. J Energy Storage 2018;20: 590–604.

[30] Dubey P. Global Battery Energy Storage Market to Grow by 7% to Reach $13.13bn by 2023, Says GlobalData; May 2019. [Online]. Available: <https://informedinfrastructure.com/47417/global-battery-energy-storage-market-to-grow-by-7-to-reach-13-13bn-by-2023-says-globaldata/> [accessed: 10- Sep- 2019].

[31] Pitz-Paal R, Amin A, Oliver Bettzuge M, Eames P, Flamant G, Fabrizi F, et al., Concentrating Solar Power in Europe, the Middle East and North Africa: a review of development issues and potential to 2050. J Sol Energy Eng 2012; 134.

[32] Zickfeld F, Wieland A. Perspectives on a sustainable power system for EUMENA”, Dii GmbH; June 2012.

[33] Pistoia G. Lithium-ion batteries, advances and applications. Elsevier; January 2014.

[34] EASE - European Association for Storage of Energy, “Lithium-Ion Battery, Electrochemical Energy Storage”, Energy Storage Technology Descriptions.

[35] Hesse HC, Schimpe M, Kucevic D, Jossen A. Lithium-ion battery storage for the grid - a review of stationary battery storage system design tailored for applications in modern power grids. Energies 2017;vol. 10(12) 2107.

[36] Hidalgo-Leon R, Sanchez C, Leon J, Jacome-Ruiz P, Wu J, Ortiz D. A Survey of Battery Energy Storage Systems (BESS), applications and environmental impacts in power systems. In: 2017 IEEE second ecuador technical chapters meeting (ETCM); October 2017. p. 1–6. https://doi.org/10.1109/ETCM.2017.8247485.

[37] IRENA - International Renewable Energy Agency, “Electricity Storage and Renewables: Costs and Markets to 2030”; October 2017.

[38] Fitzgerald G, Mandel J, Morris J, Touati H. The Economics of Battery Energy Storage: how multi-use, customer-sited batteries deliver the most services and value to customers and the grid”, Rocky Mountain Institute; September 2015.

[39] EASE - European Association for Storage of Energy, EERA - European Energy Research Alliance, “European energy storage technology development roadmap towards 2030”; March 2013.

[40] Erdinc O, Paterakis NG, Catalao JPS. Overview of insular power systems under increasing penetration of renewable energy sources: opportunities and challenges. Renew Sustain Energy Rev 2015;52:333–46.

[41] Clean Horizon Consulting, ”Marches du stockage d’energie. Opportunites amont compteur”, 3eme conference nationale Eurexpo, March 2017.

[42] IRENA - International Renewable Energy Agency, ”National Energy Roadmaps for Islands”, 2016.

[43] Pratt D. Taking smart to the edges of the world. PV Tech Power 2018;15:98–101.

[44] Flaherty N. “18 MW Tesla battery storage project powers up in Belgium”, eeNews; May 2018. [Online]. Available: <https://www.eenewseurope.com/news/18mw-tesla-battery-storage-project-powers-belgium> [accessed: 10- Jan- 2019].

[45] Apostolos GG. “European Union’s vision of Clean Energy for all European islands. RAE’s approach on the interconnections of the isolated Greek islands.”, PAE RAE; September 2018.

[46] Plavsic T. “The Future of Transmission System and Power System Operation in Croatia”, HOPS; November 2018.

[47] Navigant Consulting, “Energy Storage Trends and Opportunities in Emerging Markets”, Energy Sector Management Assistance Program, Conference Edition; 2017.

[48] Aghahosseini A, Bogdanov D, Breyer C. “The MENA Super Grid towards 100% Renewable Energy Power Supply by 2030”. In: 11th International energy conference, Tehran (Iran); May 2016.

[49] Simpson J, Shelton C. The rise of battery storage and its implications for the renewables sector; July 2018. [Online]. Available: <https://gulfbusiness.com/rise-battery-storage-implications-renewables-sector/> [accessed: 10- Jan- 2019].

[50] CNESA - China Energy Storage Alliance, ”Energy Storage Market Developments in the Middle East”; June 2018. [Online]. Available: <http://en.cnesa.org/featured-stories/2018/6/15/energy-storage-market-developments-in-the-middle-east> [accessed: 10- Jan- 2019].

[51] IRENA - International Renewable Energy Agency, “Policies and Regulations for Renewable Energy Mini-Grids”; November 2018.

[52] Navigant Consulting, “Market Data: Microgrids. Annual Capacity and Implementation Spending by Geographic Region, Market Segment, and Business Model”; July 2018.

[53] Microgrid Media, “Africa Microgrids”. [Online]. Available: <http://microgridprojects.com/africa-microgrids/> [accessed: 12- Jan- 2019].

[54] Interact Analysis, “Lithium-Ion Battery Market Poised for Strong Growth in Europe; Energy Storage Applications will be Fastest Growing Sector”; June 2019. [Online]. Available: <https://www.interactanalysis.com/lithium-ion-battery-market-poised-for-strong-growth-in-europe> [Accessed: 16- Aug- 2019].

[55] Belderbos A, Delarue E, Kessels K, D’haeseleer W. “The levelized cost of storage critically analyzed and its intricacies clearly explained”. TME Working Paper - Energy and Environment; December 2016.

[56] Denholm P, Margolis R. The Potential for Energy Storage to Provide Peaking Capacity in California under Increased Penetration of Solar Photovoltaics. NREL - National Renewable Energy Laboratory, Technical Report; March 2018.

[57] EPEX SPOT. Market Data, European Electricity Index (ELIX); 2019. [Online]. Available: <https://www.epexspot.com/en/market-data/elix/chart/index-chart/2019-01-15/> [accessed: 15- Jan- 2019].

[58] Nationalgrid. Firm Frequency Response Review; June 2018.

[59] TenneT. FCR Manual for BSPs. Requirements and procedures for supply of FCR; November 2018.

[60] Baringa. Frequency Containment Reserve (FCR) market review; November 2017.

[61] Ofgem. Pay-as-bid or pay-as-clear pricing for energy balancing services in the Balancing Mechanism.

[62] The Energyst. Battery Storage. A business case for battery storage?; 2017. [Online]. Available: <https://theenergyst.com/battery-storage-a-business-case-for-battery-storage/> [accessed: 16- Jan- 2019].

[63] Fleer J, Zurmuhlen S, Meyer J, Badeda J, Stenzel P, Hake J, et al. Price development and bidding strategies for battery energy storage systems on the primary control reserve market. In: 11th International renewable energy storage conference, ElSevier. Energy Proc 2017; 135:143–57.

[64] Coyne B. Can the Balancing Mechanism offset FFR price erosion?; September 2018. [Online]. Available: <https://theenergyst.com/can-balancing-mechanism-replace-ffr-price-erosion/> [accessed: 16- Jan- 2019].

[65] Jomaux J, Latiers A, De Jaeger E. Cost-based dimensioning of Battery Energy

Storage and energy management system for Frequency Containment Reserves provision. PES General Meeting - Denver; July 2015.

[66] EPEX SPOT, ”Continuous Markets: Intraday and Strips”. [Online]. Available: <https://www.apxgroup.com/trading-clearing/continuous-markets-intraday/> [accessed: 18- Jan- 2019].

[67] Next Flex. This is the fourth day in less than a week with period of high imbalance market prices in Belgium; October 2017. [Online]. Available: <https://www.engie-nextflex.com/high-imbalance-prices-in-belgium/> [accessed: 19- Jan- 2019].

[68] Breeze P. The Cost of Power Generation. The current and future competitiveness of renewable and traditional technologies. Business Insights; 2010.

[69] CEER - Council of European Energy Regulators. Key support elements of RES in Europe: moving towards market integration. CEER report; January 2016.

[70] Endesa. Latest Electricity and Gas Rates; July 2018.

[71] Stark. Quick guide to DUoS and TNUoS electricity bill charges; March 2017.

[72] Pace A, Lord J, Edwards T, Davison K. A review on embedded benefits accruing to distribution connected generation in GB. Cornwall Energy; May 2016.

[73] Havenpower. Electricity Market Reform. [Online]. Available: <https://www.havenpower.com/help/electricity-market-reform/> [accessed: 19- Jan- 2019].

[74] Nationalgrid. Introduction to Triads; September 2015.

[75] Deign J. Spain Abolishes the ’Tax on the Sun., Green Tech Media; October 2018. [Online]. Available: <https://www.greentechmedia.com/articles/read/spain-abolishes-the-tax-on-the-sun#gs.8uq1d5> [accessed: 19- Jan- 2019].

[76] Xu T, Wang W, Gordin ML, Wang D, Choi D. Lithium-ion Batteries for Stationary Energy Storage. JOM 2010;62(9).

[77] ACEEE - American Council for an Energy-Efficient Economy. “Factors That Can Contribute to Cost Reduction of Lithium-Ion Batteries for Personal Vehicles”.

[78] Eckhouse B. “The Battery Boom Will Draw $620 Billion in Investment by 2040”. Bloomberg; November 2018. [Online]. Available: <https://www.bloomberg.com/news/articles/2018-11-06/the-battery-boom-will-draw-1-2-trillion-in-investment-by-2040> [accessed: 21- Jan- 2019].

[79] Kesler SE, Gruber PW, Medina PA, Keoleian GA, Everson MP, Wallington TJ. Global lithium resources: relative importance of pegmatite, brine and other deposits. Ore Geol Rev 2012;48:55–69.

[80] Rodrigues EMG, Godina R, Santos SF, Bizuayehu AW, COntreras J, Catalao JPS. Energy storage systems supporting increased penetration of renewables in islanded systems. Energy 2014;75:265–80.

[81] Sabihuddin S, Kiprakis AE, Mueller M. A numerical and graphical review of energy storage technologies. Energies 2014;8:172–216.

[82] Pratt D. Fascinating challenges overcome by Vattenfall as UK EFR battery goes online. Energy Storage News; May 2018. [Online]. Available: <https://www.energy-storage.news/news/fascinating-challenges-overcome-by-vatenfall-as-uk-efr-battery-goes-online> [accessed: 16- Aug- 2019].

[83] Madlener R, Kirmas A. Economic viability of second use electric vehicle batteries for energy storage in residential applications. Energy Proc 2017;105:3806–15.

[84] Canals Casals L, Amante Garcia B, Canal C. Second life batteries lifespan: rest of useful life and environmental analysis. J Environ Manage 2018;232: 354–63.

[85] Official Journal of the European Union, ”Commission regulation (EU) 2016/631. Establishing a network code on requirements for grid connection of generators”; April 2016.

[86] EASE - European Association for Storage of Energy, ”Energy Storage in the Network Codes”; March 2018.

[87] Eurelectric, ”High level questions to the ELectricity Coordination Group on storage”; October 2018.

[88] IRENA - International Renewable Energy Agency, ”Renewable Energy Prospects for the European Union”; February 2018.

[89] TenneT. Market Review 2017. Electricity market insights; March 2018.

[90] Bloomberg New Energy Finance, ”Changing Business Models for European Renewable Energy”, Presentation at BNEF; January 2018.

[91] Lippert M. Li-ion energy storage takes microgrids to the next level. Renew Energy Focus 2016;17(4):159–61.

[92] Aghaie H. Estimating the resource adequacy value of demand response in the German electricity market. Austrian Institute of Technology; June 2017.

[93] Polymeneas E, Tai H, Wagner A. Less carbon means more flexibility: recognizing the rise of new resources in the electricity mix. McKinsey & Company; October 2018.

[94] Finzel H. Germany go-ahead for ’virtual battery’ grid balancing plan. Energy Storage Publishing; December 2018.

[95] Poeh N. Lithium Ion in the Data Center?, CoreSite, November 2018. [Online]. Available: <https://www.coresite.com/resources/blog/november-2018/lithium-ion-in-the-data-center> [accessed: 21- Jan- 2019].