Use cases for stationary battery technologies: A review of the literature and existing projects

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Abstract

In electricity systems with a high penetration of wind and solar power generation, electricity storage can be employed to balance power supply and demand. In recent years, stationary batteries are receiving a particularly high degree of attention as they can be used to provide several services in modern electricity systems. However, while a rising number of such battery systems are deployed globally, academic literature has not addressed the trends in deployment of these battery technologies. Thus, this study strives to address this gap by identifying and describing the most attractive use cases for stationary battery technologies on mainland and island electricity systems in two steps. First, the existing literature on applications, profitability and use cases of battery technologies has been reviewed. Second, based on analyses of a database of battery installations and of 26 interviews with industry and academia experts, the six most prevalent use cases have been identified and are presented in this paper. We describe these use cases in detail, highlighting their drivers, sources of value creation and risks.

Key Words: Energy storage; use case; battery; economics; projects; database

1 Introduction

With increasing emphasis on reducing global carbon emissions and promoting universal energy access [1], and long-term concerns over fuel price volatility and energy security [2], renewable energy technologies, with their fast declining costs [3,4], are becoming an increasingly important part of the future energy system [5]. However, integrating high shares of variable renewable energy sources into power systems can prove to be a challenge [6–8]. Out of the several available flexibility measures [9–12], energy storage technologies are particularly promising response options because of their unique ability to decouple power generation and load over time [13].

Due to their favorable technological characteristics and potential for cost reduction, electrochemical batteries are receiving an increasing amount of attention within industry, politics, and academia in recent years. Their fast response time, scalability and modularity enables them to serve both power and energy applications and thus provide a wide range of services in on-, off-, and weak-grid situations [14]. As a result, significant activity is being seen in this sector, with a large number of battery installations being deployed across countries [15].

Nevertheless, to support investment in and deployment of stationary battery technologies, investors and policymakers need to have a thorough understanding of viable use cases applying these technologies [16]. Use cases have been defined as “groups of (or sometimes individual) services that are provided by a single energy storage system” [17]. As battery technologies become more mature, the question of how use cases (or combinations of applications) can maximize the value created by battery installations to make them economically viable in real contexts is gaining more emphasis [18–20]. While the academic literature describes the technical characteristics of battery technologies, the various applications that can be served using them, as well as the theoretical profitability of the applications in different contexts, it does not systematically identify viable use cases for stationary battery technologies and the factors influencing them. Hence, there is a need for a review of use cases for stationary battery technologies based on empirical evidence. To address this gap, in this paper, we strive to identify and describe the most attractive use cases for stationary battery technologies on mainland and island electricity systems across different applications and geographies.

As the first step towards identification of viable use cases, we review the literature on profitability of energy storage applications for stationary battery technologies (Section 2). It is found that the studies are inconsistent in terms of the definition and nomenclature of different energy storage applications. To address this, we review different classification schemes and studies reviewing energy storage applications on mainland and island electricity systems, and adopt a mutually exclusive and collectively exhaustive classification scheme [21]. Further, we present the difficulties in identifying viable use cases from the existing literature, due to their limited geographical focus, the segregation between studies on mainland and island contexts, and scarcity of empirical evidence in existing studies. Second, we develop a database of energy storage projects deployed globally and pursue expert interviews to get a perspective on trends, and to identify viable use cases across different geographies (Section 3). The database is used to observe trends in applications, their combinations and the geographies in which they occur. This information is enriched using expert interviews in which the underlying drivers and risks for the use cases are identified. The obtained results are presented and discussed in Section 4. Section 5 concludes by stating possible avenues for future research while summarizing the paper’s principle contributions.

2 Literature review

For the purpose of identification of use cases for stationary battery technologies, we reviewed peer-reviewed academic publications as well as grey literature (technical reports and white papers by research laboratories, agencies, consultancy, and industry analysts), primarily because storage is a fast-moving industry, and a lot of up-to-date information regarding developments in energy storage applications can be found only in grey literature. As a starting point for the identification of use cases for stationary battery technologies, we reviewed studies evaluating the profitability of energy storage technologies. An overview of the results of recent studies performing a comparative analysis of energy storage applications and use cases is provided in Table 1, followed by some key observations from these studies.

Table 1 Publications on profitability of energy storage technologies and use cases

Author, year	***Technologies in focus***	***Applications/Use cases assessed***	***Geography***	***Main outcomes***[1]
RMI, 2015 [20]	Lithium ion	Commercial demand-charge management, Distribution upgrade deferral, Residential bill management, Solar self-consumption	US	By combining a primary service with a bundle of other services, batteries become a viable investment. Distribution upgrade deferral is the only use case without positive economics.
Battke and Schmidt [21]	Vanadium redox flow	Wholesale arbitrage, area & frequency regulation, end-consumer arbitrage, end-consumer reliability and increase of self-consumption	Germany	Vanadium redox flow is not profitable under any application. Area & frequency regulation has the highest value, followed by increase of self-consumption, end-consumer power Reliability and wholesale arbitrage.
Agora Energiewende, 2014 [22]	Lead acid, lithium ion, sodium sulphur and flow batteries	Area & Frequency Regulation, Reserve Capacity, Increase of Self-consumption	Germany	Batteries can be better than the use of conventional generation for area and frequency regulation, and are profitable of increase of self-consumption
Bradbury et al, 2014 [23]	Pumped hydro, compressed air, flywheels, capacitors, super-capacitors, superconducting magnetic energy storage, lead acid, nickel–cadmium, lithium-ion, sodium-sulfur, sodium nickel chloride, zinc-bromine, polysulfide bromide, and vanadium redox	Wholesale Arbitrage	US	IRR >10% possible in best case estimates for PHS in every market, CAES in every market but ISO-NE, ERCOT even in worst case, EDLC in NYISO, ERCOT, MISO and CAISO, LA in ERCOT, NaNiCl in every market but ISO-NE, in ERCOT even in worst case
RMI, 2014 [24]	Lithium ion	Off-Grid application with Solar PV plus battery storage on the mainland – similar to Increase of Self-consumption	US	For commercial sites: Profitable in Hawaii in 2015 in all scenarios, in New York by 2020 in all but the base case scenario and in California in two scenarios. For residential sites: Profitable in Hawaii in 2015 in 2 scenarios and in New York and California in 2020 in the combined improvement scenario.

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[1] For economic performance of storage technologies

Denholm et al, 2013 [25]	Generic storage device	Energy arbitrage, frequency regulation, spinning reserves	US	Regulation reserves have the highest value ($109.8/kW-yr), followed by spinning reserves ($65.2/kW-yr) (calculated for a 100 MW device) and arbitrage ($34.9/kW-yr for 300 MW device). Profitability has not been calculated, but calculated break-even capital costs are higher than typical costs reported in literature.
Akhil et al, 2013 [18]	Pumped hydro, Compressed Air Sodium-sulfur, Sodium-nickel-chloride Batteries, Vanadium Redox, Iron-chromium, Zinc-bromine, Zinc-air, Lead-acid, Flywheel, Lithium-ion batteries	18 applications in 5 umbrella groups: bulk energy services, ancillary services, transmission infrastructure services, distribution infrastructure services, customer energy management services	US	Installed cost ($/kW installed), levelized cost of energy (LCOE) per kilowatt-hour ($/kWh) of delivered energy and per kW of discharge capacity ($/kW-yr) are calculated for different technologies and applications.
Sigrist et al. (2013) [26]	Unspecified energy storage system	Frequency regulation and peak shaving	Canary islands	Using energy storage is estimated to yield an IRR of 8% over a lifetime of 15 years in one of the analysed cases.
Lal and Raturi (2012) [27]	Lead acid and lithium ion batteries	Renewable energy time shift	Fiji	The LCOE of optimum hybrid solution is found to be Fijian $761/MWh. However, no comparison is made with the baseline for this optimal configuration.
Chen et al. (2011) [28]	Lead acid and vanadium redox batteries	Renewable energy time shift	Generic microgrid	Optimally sized lead acid batteries are found to have an NPV of $30.11, while the NPV for VRB is $13708 for the same system.
EPRI, 2010 [29]	Pumped hydro, CAES, NaS, lead acid, advanced lead acid, Zn-Br, Vanadium redox, Fe/Cr redox, Li-ion, flywheels	Wholesale Energy Services, Renewables Integration, Stationary T&D Support, Transportable Storage for T&D Support, Distributed Energy Storage Systems, ESCO Aggregated Systems, C&I Power Quality and Reliability, C&I Energy Management, Home Energy Management , Home Backup	US	The only applications where benefits may exceed costs are T&D support while also serving regulation and local capacity, or commercial reliability applications where a large value is placed on reliability (such as commercial data centers)
Eyer and Corey. 2010 [19]	Technology-neutral framework	Electric Energy Time-shift, Electric Supply Capacity, Load Following, Area Regulation, Electric Supply Reserve Capacity, Voltage Support, Transmission Support, Transmission Congestion Relief, Transmission & Distribution (T&D) Upgrade Deferral, Substation On-site Power, Time-of-use (TOU) Energy Cost Management, Demand Charge Management, Electric Service Reliability, Electric Service Power Quality, Renewables Energy Time-shift, Renewables Capacity Firming, Wind Generation Grid Integration	US	Benefits calculated for applications using technology-neutral assumptions, with the highest benefit being for area regulation ($785-2010/kW), followed by electric energy time shift ($150-1000/kW) and T&D upgrade deferral ($481-1155/kW for one year).
Kaldellis et al. (2010) [30]	Lead acid, NaS, Li-ion, fuel cells, flow cells and flywheels	Renewable energy time shift	Typical small Greek island	PHS and NaS are found to be the most cost competitive technologies, with LCOE as low as 0.19 EUR/kWh, as compared to the cost of conventional generation at 0.31 EUR/kWh.

There are certain common observations which can be made from the studies presented in Table 1. One of the common conclusions across the studies is that the profitability of wholesale electricity arbitrage is lower as compared to other applications, and might need to be combined with other benefits to improve the economic viability of energy storage. Frequency regulation is found to be the application leading to the highest profits, especially in markets where it is valued highly (e.g. PJM Interconnection in the US). However, while the studies analyze a number of applications for different geographies and technologies, it is seen that there is no consensus on the nomenclature of energy storage applications, leading to difficulties in comparison across studies and ensuring exhaustiveness in terms of applications considered.

To arrive at a consistent and comprehensive definition and nomenclature of storage applications, we examine existing studies which qualitatively review and classify energy storage applications. Several studies such as Masiello et al [31], Dunn et al [32], Poullikkas [33], Koohi-Kamali et al [34], Divya and Østergaard [35] and Beaudin et al [36] provide overviews of stationary battery technologies, their performance and applications, often illustrated by examples from real world projects. Masiello et al [31] discuss existing and hypothetical business models for energy storage, along with the complexities involved in their deployment and operation from a regulatory and business perspective. Poullikkas [33] provides an overview of energy storage applications with a list of 50 operational and planned large scale battery systems. Looking specifically at applications on small islands and microgrids, Koohi-Kamali et al [34] describe “applications in microintelligent power grids” as a separate category of applications, focusing on grid-connected microgrids for power reliability. Additionally, there are several studies which provide an overview of applications of energy storage technologies specifically on island and remote microgrid systems: IRENA [37] provides a theoretical qualitative overview of the capabilities of energy storage technologies on islands. Wichert [38] provides a review of design, operation, configurations and sizing of stand-alone PV-diesel hybrid energy systems. Chauhan and Saini [39] provide a qualitative review of storage technologies, sizing methodologies and control systems for integrated renewable energy systems in standalone applications. Further, Medina et al [40] provide a qualitative overview of applications based on 5 projects. Overall, it is seen that there is a division between studies focusing on energy storage applications on mainland and island contexts. Further, consensus over how to define and name applications is found to be lacking.

Looking at the studies which classify energy storage applications, we observe a trend of classifying applications on the basis of certain parameters such as the time scale of energy storage, location of the application along the value chain, or the source of value creation (Table 2). However, due to the lack of consensus about the parameters for classification of energy storage applications, and about how to define these parameters (e.g. what is meant by ‘short’ or ‘medium’ time scales), different studies feature varying numbers of identified applications for energy storage.

In this study we choose to follow the categorization on the basis of value creation and location in the energy value chain as defined in Battke and Schmidt [21] (Figure A.1). Applications are classified on one hand on the basis of the value that they create (power quality, power reliability, increased utilization of existing assets, and arbitrage), and on the other by their location in the value chain (generation, transmission and distribution, and end consumer). Each of the fourteen applications is thus defined by a combination of these two parameters (Table A.1). For example, RET smoothing is a power quality application located at the generation level. By considering all such unique combinations, this classification scheme is mutually exclusive and collectively exhaustive.

Even within this classification scheme, it is important to note that mainland and island contexts, having different technical characteristics, require different sets of applications to be prioritized. There is, to date, no study which provides an overview of the most prevalent use cases for stationary battery technologies, while recognizing the distinction between mainland and island contexts. Another shortcoming of the extant review studies is that they generally refer to studies calculating the profitability of storage technologies for different applications, without indicating which ones are actually being pursued in significant numbers. In terms of geographical focus, a majority of the mainland studies tend to look at the US and mainland Europe (Germany in particular). The extant island studies are very case specific and do not provide an overview of the distribution of the analyzed applications globally. Although certain review studies such as Poullikkas [33] and IRENA [46] do illustrate applications by listing projects and providing case studies for a variety of technologies and geographies, the analyses of the profitability of applications do not provide any indication of which of the applications are being pursued in significant numbers and where.

Table 2 Review of publications classifying energy storage applications

Source	*Author, year*	*Number of Applications*	*Classification Criteria*
[18]	Akhil et al. (2013)	14	Value chain
[21]	Battke and Schmidt (2015)	14	Value chain / value creation
[36]	Beaudin et al. (2010)	8	Value creation
[42]	Carnegie et al. (2013)	13	Time scale / cycling frequency
[43]	Delille et al. (2009)	12	Stakeholder / value creation
[19]	Eyer and Corey (2010)	17	Mixture of value chain and value creation
[29]	EPRI (2010)	10	Value chain
[44]	Manz and Keller (2011)	10	Power vs.energy / Discharge duration
[45]	Toledo et al. (2010)	11	Power vs.energy / Discharge duration

Summing up, the existing literature does not provide an overview of use cases for stationary energy storage technologies, on mainland and island contexts, across different geographies, and based on empirical evidence. This study addresses this gap by providing an overview of use cases which are pursued in different geographies.

3 Methodology

The following section introduces the methodology used to identify the use cases of stationary battery technologies. It is structured in two steps. In the first step, the existing knowledge from literature about the energy storage applications has been complemented with the development and analysis of a global database of energy storage projects. In the second step, interviews with experts from industry and academia are used to enrich this knowledge by understanding and validating the identified use cases, as well as their key drivers and trends.

3.1 A database on storage installations

In order to develop a holistic picture of the currently installed stationary battery projects, a database was developed and analyzed in order to get a perspective on trends in energy storage installations across the world and to identify the most frequently occurring use cases across different geographies. The database was established in two steps. First, data on energy storage projects from several sources was collected. Second, the collected data was verified and consolidated to remove inconsistencies arising from differences in nomenclature in different data sources.

3.1.1 Data collection

The database of energy storage projects compiled for this study provides information about technology, size, applications served, location, stakeholders and commissioning date of energy storage installations across the world. The US Department of Energy (DOE) Energy Storage database, containing 1156 records, was used as the starting point for the database. This database was extended by energy storage projects from several databases and project case studies from company websites.[2]

The final database, last updated in February 2015, contains 1279 energy storage projects. Out of these, 612 are battery projects totaling 1350 MW/2444 MWh of installed capacity. These are distributed across 6 technologies and 42 countries. In the following sections, the primary focus of the analysis will be on stationary battery installations listed in the database.

3.1.2 Data verification and preparation

There are some inconsistencies in nomenclature of energy storage technologies and applications in records taken from different sources. After incorporating them in the database, key data fields such as installed capacity, technology, application and project description were checked for completeness and consistency by manually going through the records. Empty or incorrectly filled records were corrected after conducting web searches specific to the projects in question, followed by verification of the data during the interviews wherever possible.

Several data fields were combined and adapted to keep the terminology consistent within the database and with previous research, in order to aid in further analysis of the entries in the database. For example, the organization of the applications was done on the basis of source of value creation and location along the value chain, as described in section 2.1. Further, a search was done for keywords such as “island”, “microgrid”, “standalone” and combinations and variations thereof to isolate the projects of projects on islands and microgrid systems from mainland projects. A description of the important data fields will be discussed in the following paragraphs.

Applications: The projects in the US DOE database have been classified into 27 different “service/use cases”, which are defined as “the benefits provided by the energy storage system. Services refer to individual benefits and may come from direct market participation or reduced/deferred cost relative to the status quo. Use cases are groups of (or sometimes individual) services that are provided by a single energy storage system.” [17]

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[2] These include, among others, the Energy Storage Database of the European Association for Storage of Energy, Energy Excelerator Hawaii Database, Navigant Research Microgrid Deployment Tracker, and case studies from the IRENA Electricity Storage and Renewables for Island Power report, the Energy Storage Association, Trojan Battery and Optimal Power Solutions. Due to the nature of the sources used for the database, it may have a bias towards large-scale installations that can be regarded as “storage projects” rather than conventional renewable power projects, which incorporate energy storage as part of the system. To address this bias, the final analysis does not rely on just the database, but draws extensively from the expert interviews to obtain a complete picture.

The listed “service/use cases” and applications were cross-checked with the project description in the database, in publically available case studies of the specific project, and on company websites to ensure that they correspond to the application being served in the actual project. Following this, a translation scheme (Table A.3) was developed and employed to assign the 14 applications as defined by Battke and Schmidt [21] to each project, in order to enable classification of the projects according to the main source of value creation as well as location in the power system value chain (Table A.1).

Technologies: The compiled records in the database belong to 24 different technologies. These include electrochemical storage (batteries, fuel cells, hydrogen storage), mechanical storage, (flywheels, compressed air systems) and thermal (heat and ice) storage.

However, there are some ambiguities about the nomenclature in different sources due to the overlapping of different levels of classification of certain technologies. That is, while certain projects have a higher level of classification (e.g. lithium ion battery), others have been categorized into sub-types (e.g. lithium iron phosphate battery). A translation scheme was employed to remove these ambiguities and to maintain a consistent level of classification of technologies, with each project associated with one of the following seven major categories – lithium-ion, lead acid, sodium salt, flow batteries, nickel based, metal air and electrochemical (unspecified).

3.1.3 Analysis

An important step towards the identification of use cases is a descriptive quantitative analysis of the project database, which has been performed to derive trends regarding energy storage installations: The distribution of projects across the most important parameters – namely technologies, geographies and applications – and interrelationships between these parameters has been analyzed. Trends such as the most common combinations of applications and the frequency of applications across geographies have been derived. The main observations from the database analysis, along with some illustrative charts are given in section 4.

3.2 Interviews

A series of telephonic and personal interviews was conducted to enrich the information obtained from the database analysis by developing a more detailed understanding of use cases for stationary battery storage, along with their key drivers and trends.

In order to sample potential interview partners, the stakeholders (technology providers, developers, integrators, utilities etc.) in the project database were identified. Interviewees from research institutions were also included. Interview requests were sent out to ensure adequate coverage among actors involved in each of the identified business cases across several geographies, resulting in a total of 26 interviews being conducted between July and September 2014 (Table A.2).

The interviews were semi-structured, with questions for each interview tailored based on the information about the projects in the database and related documents. Each interview lasted between 30 and 90 minutes, with at least two interviewers conducting the interview and taking notes of the responses. In several cases, additional data sources were provided by the interviewees in the form of reports, documents and presentations. The notes taken during the interviews, along with the other documents were used to supplement the trends derived from the storage database, and to arrive at a detailed understanding of use cases for stationary battery storage. Table A.2 shows an overview of the different interviewees and their position within the organization, grouped into the different stakeholders of the storage projects. The interviews are referred to in section 4.2 to describe the use cases in more detail.

Taking together the insights gained from the analyses of the database (Section 4.1), the information gathered during the interviews fed into the use cases identified and presented in Section 4.2.

4 Results and Discussion

The results of the analyses of the database are presented in this section, which proceeds in two steps. First, the key trends regarding energy storage installations derived from the database described in Section 3.1 are presented. An analysis of the most commonly served applications, combined with an understanding of the context in which they are deployed is necessary for the identification of viable use cases. Hence, in section 4.1, we focus on different technologies, applications, and geographies[3]. Second, the identified use cases are described in detail in section 4.2. In both subsections we present results for battery installations in mainland power systems separately from results for battery installations on island and microgrid systems.

4.1 Analyses of existing stationary battery installations[4]

Figure 1 shows the shares of different technologies in all mainland and island projects in the database. Lithium ion batteries make up for more than half of the projects. This may be because of their ability to serve both energy and power applications to a certain extent. This makes them particularly suited for integration of renewable energy, frequency regulation, and also to serve multiple applications. It also shows that NaS batteries usually have a comparatively high energy capacity, since their share in installed capacity in MWh is 43% and that in MW is just 30.6%.

4.1.1 Mainland electricity systems

Mainland electricity systems are characterized as being large, interconnected systems, typically with high system inertia, the ability to balance loads with generation resources over large geographic areas, and the consequent possibility of having competitive markets for power and ancillary services.

Applications: The projects in the database, when classified according to the primary application served by the storage technology, as well as the combination of primary and secondary applications (Figure 2), show that the largest share of projects (36%) is dedicated to arbitrage applications, majority of which involve electric bill management at the consumer level (23%). Other applications involve wholesale arbitrage at the grid or generator level. The second largest share is dedicated to power quality applications (33%) – realized at the grid level (19%) by provision of services such as area and frequency regulation (16%) and voltage support (3%) or at the generation level by RE output smoothing and ramping (14%).

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[3] A geography here is defined as a region with similar regulatory, climatic and energy system characteristics and therefore can refer to the national or sub-national level.

[4] For the analyzed parameters, the illustrative charts have been organized to depict the percentage of total number of projects and percentage of total installed capacity in MWh and MW. Going from left to right, the relative proportion between number of projects and installed capacity in MWh gives an indication of the average project size. The relative proportion between installed capacity in MWh and installed capacity in MW gives an indication of whether they are used primarily for energy or power applications.

69% of the projects in the database have secondary applications listed. Figure 2 also indicates how often certain combinations of applications are observed in the database. It is seen that power quality applications on the generation level (RET smoothing) are combined most frequently with arbitrage – a total of 34 times. The second most common combination, which appears 20 times, is that of consumer power reliability with increased utilization of generation assets – typically residential solar PV.

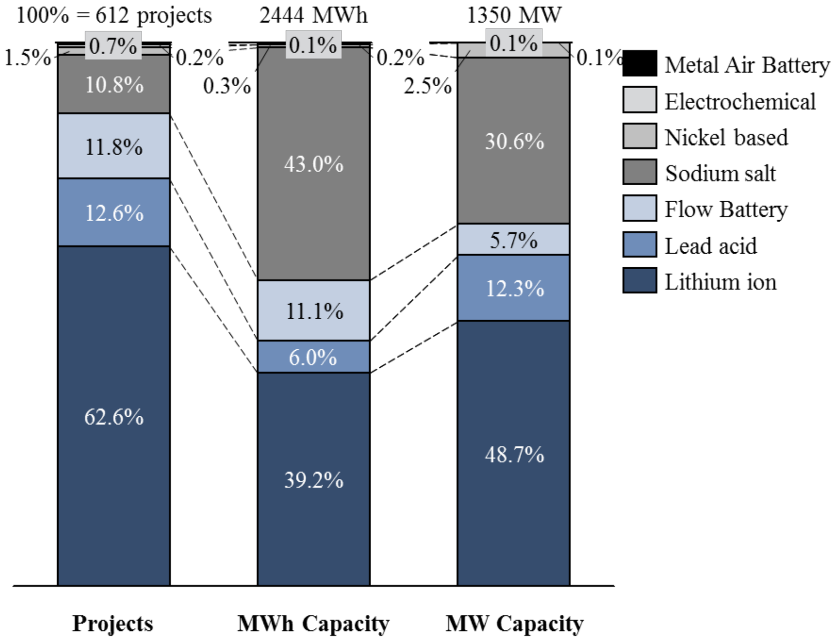

Figure 1 Split of projects by technology in project database

Geographies: In order to develop an understanding of the context in which the most commonly served applications are deployed, the database is analyzed across geographies by the number of projects and by battery capacity in Megawatts (MW). Figure 3 shows that more than half of the projects are developed in the US[5]. In terms of capacity, the US accounts for less than half of the overall capacity, which means that the database shows comparatively more small scale projects there than in other countries. The opposite is true for Japan and Italy, where large scale projects dominate.

The most important geographies and applications for electrochemical energy storage (in terms of project numbers) can be seen in Figure 4, and four key observations are made on this basis. First, looking at Germany, a large proportion of the projects provide frequency control. Examples are the WEMAG Battery Park in Schwerin (5MW/5MWh Li-ion battery), the Younicos and Vattenfall project in Berlin (1MW/6MWh NaS battery) and the project in Feldheim (10MW/5MWh Li-ion battery).[6] Second, the primary drivers for energy storage projects in the US, namely in the CAISO (California Independent System Operator), ERCOT (Electric Reliability Council of Texas), NYISO (New York ISO) and PJM (Pennsylvania-New Jersey-Maryland Interconnection) market areas are examined in more detail. In PJM many projects are developed to provide area and frequency regulation,

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[5] This is likely to increase significantly in the near future with the implementation of the California Public Utilities Commission's (CPUC) procurement target of 1.325 GW of energy storage (excluding pumped hydro) by 2020 [81].

[6] The other important pillar of energy storage in Germany is increased self-consumption [22]. This cannot be seen in the figure though, since these projects are highly distributed and of small size and are not included in the database. This topic will be detailed further through the expert interviews.

known as Dynamic Regulation (RegD) in PJM terminology. This is largely driven by FERC (Federal Energy Regulatory Commission) order 755, which allows higher compensation for faster responding balancing resources such as batteries, flywheels and demand response. Prominent examples are the Laurel Mountain project in West Virginia, developed by AES (32MW/8MWh Li-ion battery), or the project in Ohio developed by RES Americas (4MW72MWh Li-ion battery). Third, in the CAISO market, more than half of the developed projects are utilized for end-consumer arbitrage, many of which are developed by the company Green Charge Networks. These projects utilize Li-ion batteries with the main objective to reduce customer demand charges (for more details, refer to section 4.2.1). In addition, individual batteries are aggregated into pools to participate in demand response programs. Fourth, the same holds for the NYISO market, where the focus on reducing customer demand charges is just as evident. In ERCOT no clear focus for the projects can be seen because of the low number of projects in the database. The key result of this analysis is that the distribution of applications varies significantly across different geographies, depending on varying regulations, tariffs and incentives. Thus it is important to note that while identifying viable use cases, one cannot make generalized statements about applications in isolation, but one also needs to consider the location and regulatory environment.

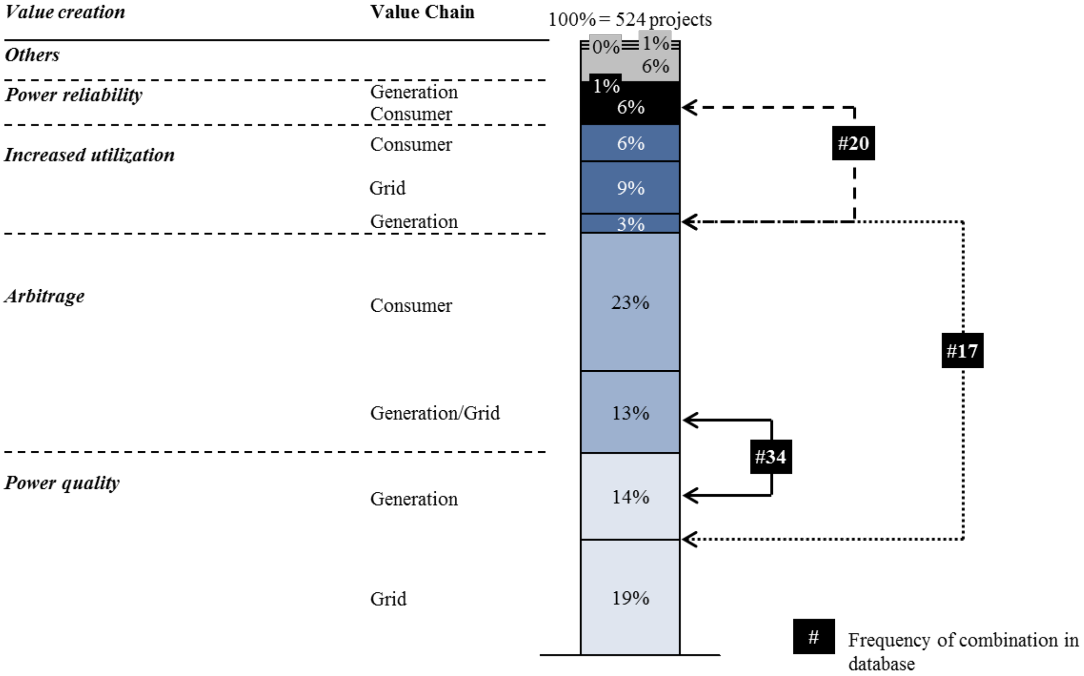

Figure 2 Split of mainland projects by application

4.1.2. Island and microgrid electricity systems

While there are no commonly accepted standard definitions of small island and microgrid systems, several definitions exist for different purposes. For example, for the purpose of evaluating the global potential of energy storage systems on small islands, Blechinger et al. [47] define small islands on the basis of number of inhabitants. The European directive 2009/72/EC does so on the basis of annual energy consumption. Other studies such as Ton and Smith [48] and Lopes et al. [49] give functional definitions of microgrids such as “A microgrid is a group of interconnected loads and distributed energy resources within clearly defined electrical boundaries that acts as a single controllable entity with respect to the grid. A microgrid can connect and disconnect from the grid to enable it to operate in both grid-connected or island-mode” [48]. Recognizing the shortcomings of having a strict definition of microgrid and island systems based on population, energy consumption or installed capacity, and avoiding overlap with mainland applications, we identify applications of energy storage technologies arising from technical, market and regulatory conditions specific to such systems. These include low power system inertia, dependence on diesel and heavy fuel oil for power generation [50] and absence of competitive markets [51]. As an example, while increased household self-consumption is economically viable in many island settings [4], it is not specific to island and microgrid systems.

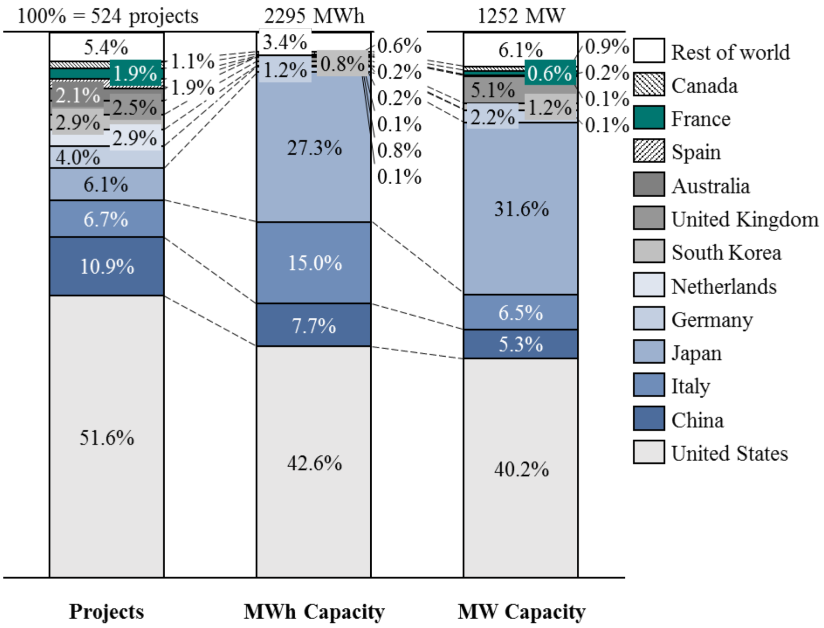

Figure 3 Split of mainland projects by geography

Applications: Similar to the analysis for mainland projects, the projects in mainland and island contexts have also been classified according to the primary application served, as well as according to the combination of primary and secondary applications. It is observed that the largest share of projects (43%) is dedicated to increased utilization of existing assets – realized by RET firming (36%) or load following (6%). The second largest share is dedicated to power quality applications (35%), which include RET smoothing (23.8%), area and frequency regulation (6.8%) and other applications such as ramp rate control, reserve capacity and voltage regulation.

The most commonly combined applications are increased utilization of generation capacity (RET firming) with RET smoothing – with 31 projects stating such a combination in their primary and secondary applications. The second most common combination is between frequency regulation and voltage control – occurring a total of 12 times.

The frequency of applications served in terms of percentage of the total number of projects has been illustrated in Figure 5.

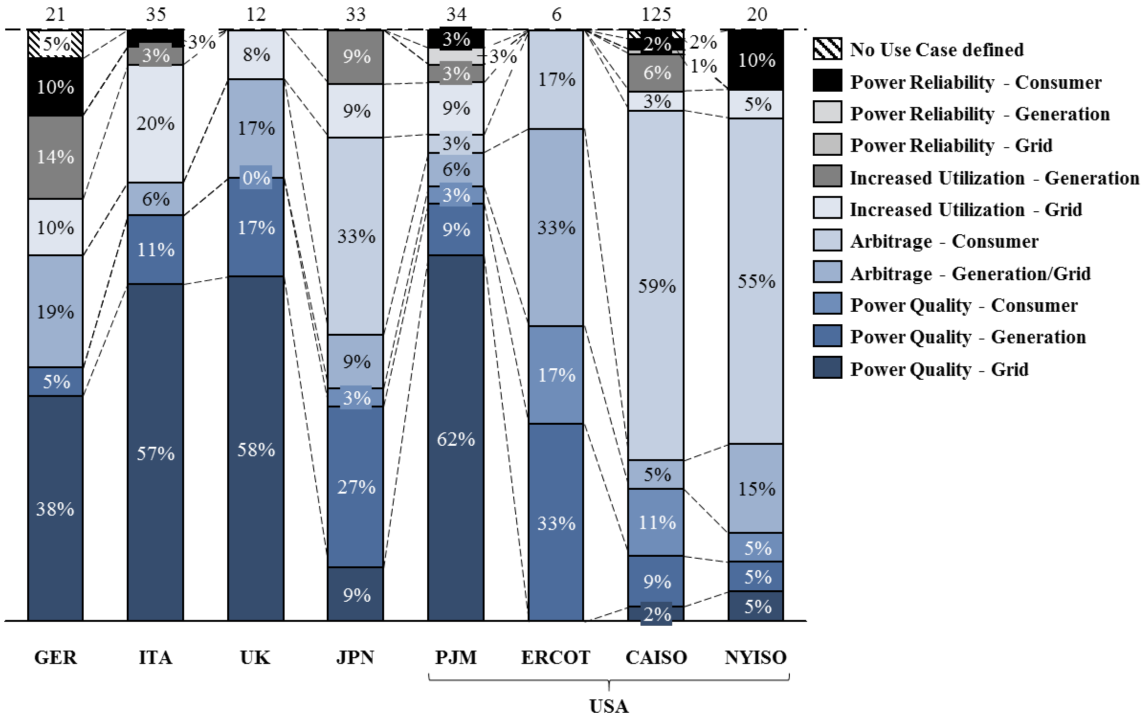

Figure 4 Distribution of applications across prominent geographies (number of projects indicated above each bar)

Geographies: As can be seen in Figure 6 the US has the highest number of projects, particularly in Hawaii. The high power rating as compared to the energy capacity of projects in Hawaii shows that most of these are sized for power applications. Closer examination of individual projects in the database shows that a majority of them are for RET smoothing, ramp rate control and area and frequency regulation (driven by regulations), or demonstration projects for grid stabilization.

Remote islands of Japan and France follow the US in terms of installed capacity. Japan has projects similar to those found on Hawaii, with a focus on RET smoothing and large-scale demonstration projects to study the behavior of energy storage technologies (primarily lithium ion and sodium sulphur) for renewable integration on island systems. Here, the focus is on sodium sulphur batteries, which is responsible for high average discharge duration (high MWh compared to MW) observed in Figure 5. The projects in France are found on the islands of the French overseas departments such as Reunion and Martinique. A majority of these projects are comprised by storage coupled with solar PV plants in order to enable constant power output (in accordance with French regulations), as well as large-scale demonstration projects on Reunion.

The remaining projects are demonstration projects on Canary Islands (Spain) and in South Korea, and hybrid microgrid projects focusing on RE time shift or reserve capacity for diesel replacement on the smaller British, Portuguese and Indonesian islands, and remote off-grid locations in Australia and India.

To sum up, large-scale projects in Hawaii, Japan and French overseas departments are driven by research and demonstration projects, regulations for storage-coupled renewables and tenders from utilities for energy storage installations for provision of grid services.

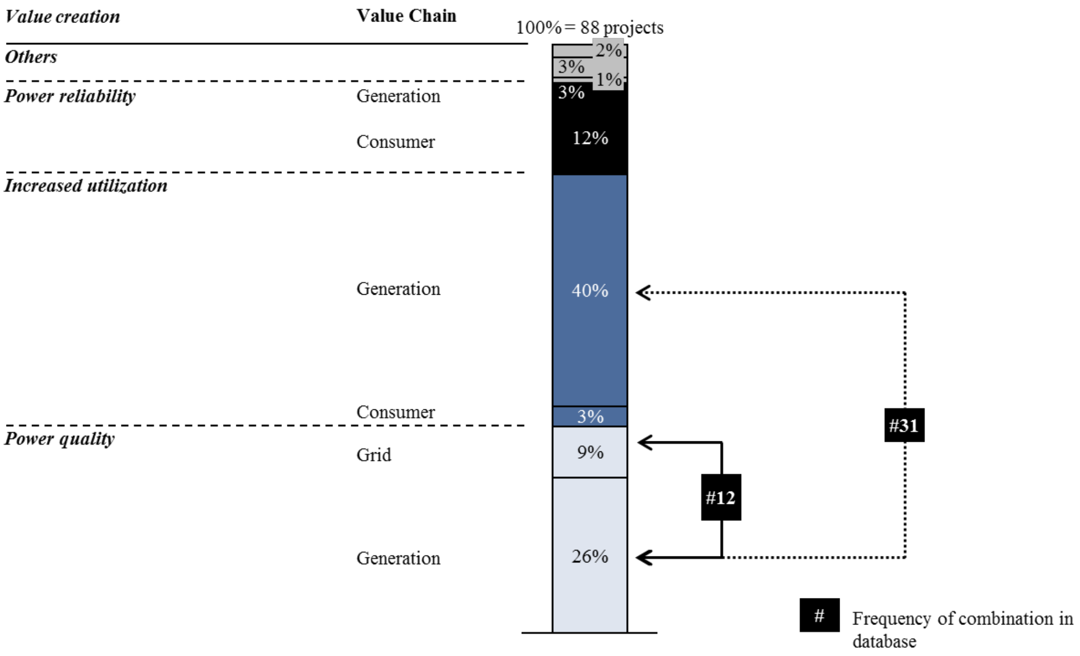

Figure 5 Split of island and microgrid projects by application in project database

Overall, it is seen that there is large diversity in terms of applications – all fourteen applications as defined by Battke & Schmidt [21] are found across different geographies in mainland as well as off-grid contexts. However, certain trends can be observed. First, there is significant activity in terms of providing end-consumer arbitrage in New York and California. Second, area and frequency regulation shows highest activity in Europe and PJM market in the US. Third, a large number of projects on island and microgrid systems are for RET firming. Fourth, the second most common application on such systems is RET smoothing, with most of the projects located in Hawaii.

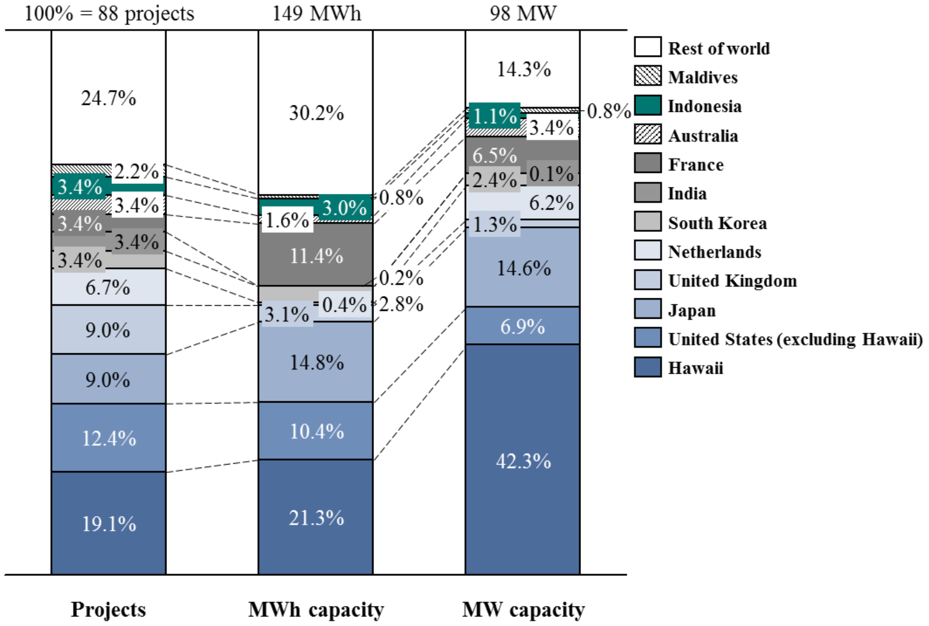

Figure 6 Split of island and microgrid projects by geography

4.2 Use cases for stationary batteries

The trends observed in the storage database have been supplemented with information from the expert interviews, resulting in the identification of six use cases. The following sections will (again distinguishing between mainland and island systems) elaborate on these use cases, giving an account of their background, the sources of value creation, and relevant geographies. This is followed by a description of the technology, operational, market and counterparty risks faced by these use cases in Table 3. The interview source is provided using the coding scheme provided in Table A.2.

4.2.1 Mainland electricity systems

Demand charge reduction

Description: Demand charges are a component of the electricity bill for commercial and industrial consumers, which is based on the peak electricity demand during the billing period. The level of investments required in installed capacity and T&D infrastructure by utilities largely depends on the peak electricity consumption. Levying demand charges is one of the ways used to cover the fixed cost of electricity provision of the utility, and to provide an incentive to commercial and industrial consumers reduce their peak consumption. The recent uptake in distributed generation leads to a decrease in energy sold per customer for the utilities, which leads to increasing pressure to change their rate structure and increased fixed and demand charges. Batteries can be used to store electricity during times when the demand is low, and can be used to meet the demand during peak hours, reducing the demand charges and leading to savings for the consumer.

Value creation: In this use case, the primary source of value creation is reduction of demand charges of a consumer by reducing the peak demand. For this, the SES must be sited at industrial or commercial end-consumers that are under such a tariff that bills separately for the maximum power demand within a month as well as the total energy consumed during that month. Secondary sources of value stem from taking advantage of time-of-use tariffs by shifting the demand to periods when electricity tariff is low. It may even be possible for storage device to provide power quality and reliability services by aggregating multiple storage devices and bidding the spare capacity into markets, e.g. demand response programs (as Stem has done in California). This is also advantageous since the average project size is rather small (between 0.1 and 1mn EUR investment volume) and aggregation increases the investment volume, reducing the transaction costs for investors [DEV].

Geographies: This business case is most interesting in geographies such as California and New York, where demand charges have risen sharply in recent years. The use case is driven by incentive programs such as the Self-Generation Incentive Program (SGIP) in California and ConEdison's Energy Storage Incentives in New York. The SGIP, aimed at promoting distributed power resources for peak load and greenhouse gas reduction, provides an incentive of $1.46/W for “advanced energy storage”. Energy Storage Incentives in New York provide $2100/kW for battery storage systems which provide peak demand reduction above 50 kW in summers. Incentives are capped at 50% of investment volume in NY and 60% in CA. These programs result in attractive returns, with project developers reporting payback periods of 3-5 years [DEV]. For example, Neubauer and Simpson [52] calculate payback periods of 3-5 years for installed system costs of $300/Wh and $300/kW using Li-ion batteries in California, given Southern California Edison’s rate structures. Nottrott et al. [53] calculate positive NPVs for Li-ion batteries for installed costs less than $400-500/kWh, when combining demand charge reduction with time-of-use optimization under San Diego Gas & Electric's rate schedule for industrial customers. Fitzgerald et al. [20] combine demand charge reduction along with time-of-use optimization and ancillary services for a hotel using Li-ion batteries in San Francisco, finding that the benefits exceed the costs for such a system.

Residential solar integration (Increase of self-consumption)

Description: In cases where the cost of generation of electricity from customer-sited generation (such as solar PV) is lower than the retail price of grid electricity, it can be more economical to maximize the consumption of the generated electricity on-site rather than feeding it back into the grid. This can be done by shifting demand patterns so that peak demand coincides with peak generation, or by using batteries to store the excess electricity and use it when required.

Value creation: The primary value is created in this use case by increasing the customers´ consumption of power generated on-site by a PV array. Secondary sources of value stem from the utilization of time-of-use tariffs, which charge different rates at certain times for the consumed energy of a customer. The storage device can also provide power reliability services for residential clients. Furthermore, additional value can be created by aggregating multiple storages to provide power quality services by bidding the spare capacity into markets[7], e.g. secondary control reserve and minute reserve (as companies such as Sonnenbatterie, E3DC and Deutsche Energieversorgung GmbH are planning to do in Germany), primary frequency control (as Caterva is doing) or other ancillary services [DEV]. Since the main value stems from an increase in self-consumption, the SES must be sited at residential end-consumers that have already installed or have the opportunity to install a PV array and where an installation of a SES would increase the self-consumed energy significantly.

Because the average project size is rather small (between three to ten thousand EUR investment volume), some project developers aggregate multiple projects so that the investment volume increases. This also allows for additional value to be captured via market participation [DEV].

Geographies: Particularly interesting geographies for this use case are Germany and Italy [UTI, DEV]. In the future it might get also interesting in California, Spain, the UK, Japan and Australia [4, DEV].

In Germany, significant deployment of SES combined with solar PV is already taking place [22]. The profitability of the storage investment increases when combined with PV today, even though a pure PV investment still has higher profitability [54]. However, the profitability is highly dependent on the regulatory environment. According to Hoppmann et al [55] the net present value of Li-ion batteries with solar PV is already positive in Germany in the case of residential buildings, and is predicted to increase with falling battery and PV module costs. This has been positively affected by the removal of the exemption from EEG-surcharge (a surcharge on consumer electricity bills to cover the costs of support for renewable power) for PV arrays larger than 10kW at residential sites. Net metering tariffs, which are common in some states in the US, make storage unattractive because the electricity can be fed back into the grid at the retail price [20,56].

The desire of consumers to reduce their dependence on utilities, thus increasing the willingness-to-pay for a storage device, is also reported to be an important driver for storage economics and might lead to further rollout

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[7] Aggregation may be required to meet minimum requirements for prequalification for markets. For example, the device has to be able to supply 1 MW power for a minimum of 15 minutes to prequalify for primary regulation market in Germany

of this use case [DEV]. In the long run, more opportunities may open up, with many PV arrays dropping out of the FiT by 2030.

Frequency regulation

Description: In order to keep the frequency of the grid alternating current within permissible limits, there needs to be a balance between demand and supply at each instant. This can be done at different time scales by adjusting power generation, using demand response or electricity storage. Primary control reserve stabilizes the system frequency in the time frame of seconds (typically, in Europe, the response time of the primary control power should be less than 30 seconds and must be delivered until the power deviation is completely offset by the secondary or tertiary control reserve), followed by secondary control reserve (time frame of seconds up to typically 15 minutes after a deviation) and tertiary control reserve (for larger incidents or longer time frames) [57]. The fast response of many battery technologies makes them quite suitable for frequency regulation. As has been reported in literature, the profitability is high, and it might be even higher for utilities when considering the portfolio effect [UTI].

Value creation: The primary value is created by participating in frequency regulation markets. Generally, the SES can be operated from any position in the value chain. Certain sites, however, might increase the possibility of generating value from additional sources. One example is the use of the remaining battery capacity for increasing consumer self-consumption, as in the case of Caterva. On the other hand, by siting the battery at an existing power generation site, grid fees can be saved.

Geographies: This use case is interesting in geographies such as Germany and the PJM market in the US, where a high value is placed on the provision of frequency regulation [DEV]. In the US, FERC order 755 (pay-for-performance regulation) specifies that ISOs need to remunerate frequency control resources appropriately based on the actual service provided, with faster and more accurate ramping resources receiving higher payment. This puts storage technologies at an advantage over other assets like power plants which are typically used for frequency regulation and cannot provide service as quickly. Avendano-Mora et al. [58] calculate a payback period of 5-6 years and a benefit to cost ratio of 1.2 for Li-ion batteries of size 5 MW or greater in the PJM market. Fares et al. [59] indicate that the net present value of a vanadium redox flow battery for frequency regulation in ERCOT ranges between \$(-100)/kW to \$1871/kW. However, this is without taking into account prices for fast-ramping regulation according to FERC order 755. In Germany, even though the value of primary reserve is high [22], there are certain regulatory barriers faced by project developers. To participate in this market, the prequalification procedure, in which the minimum technical requirements are tested, has to be carried out for each device individually. The lack of standardized prequalification for battery technologies or single types of batteries creates a barrier to entry, especially for pooled assets when each asset needs to be prequalified individually.

4.2.2 Island /microgrid electricity systems

Load following

Description: Diesel generators are the predominant power production technology used in small island grids, remote microgrids and standalone applications [37,60] because of their low capital cost, good operational flexibility, relatively quick start-up and ease of operation [61]. They have an optimal efficiency near the rated capacity (at 80-90% of rated power output) and usually should not be operated below 30% of their rated capacity. However, daily and seasonal variation in load means that it is not possible to operate at peak efficiency at all times. The introduction of renewables into existing systems further increases the cycling requirements, reduces capacity factors and efficiency of the generators and may lead to reduced plant life due to thermal and mechanical fatigue [62,63].

Energy storage devices can be used to optimize the efficiency and to reduce the run time of these generators. In a small diesel powered system, this can be done by running the generator at peak efficiency until the storage device is charged to full capacity and using the storage device to supply power to the load. Further, in hybrid systems, the operation of peak generators at part load can be avoided by using energy storage.

Value creation: In this use case, the main methods of value creation are increased diesel generation efficiency, reduced O&M costs and extended lifetime due to reduced run time of the diesel generator. In addition, the battery can also be used to integrate renewable generation sources.

This use case is particularly prevalent in the telecommunications industry in standalone power systems for telecom infrastructure with unreliable or no grid access. In such towers, the diesel generator has to be oversized, especially due to the high starting current requirement of the air condition of the towers [64]. As a result, the diesel generator needs to be oversized by a large margin to meet these requirements, resulting in a very low overall efficiency.

Geographies: Even though this use case receives scant attention in academic literature, the interviews and review of the grey literature indicate that it is particularly prevalent in countries such as India, which is currently largest growing market for telecommunication towers [65]. There were 70,000 towers in off-grid locations in 2011, out of which 73% were operating in battery diesel hybrids [66]. This share is estimated to have increased to 90% today [TEC]. Further, globally, out of an expected additional 165,000 towers in off- and bad-grid locations by 2020, about 10% will be in India [67]. According to India's Department of Telecom and the Telecom Regulatory Authority of India (TRAI), at least 50% of all rural towers and 20% of the urban towers are required to be powered by hybrid power by 2015; which should increase to 75% of rural towers and 33% of urban towers by 2020 [68].

Renewable energy integration

Description: In island and microgrid power systems with low RET penetration, the effect of additional renewable generation is similar to that of a reduction in load. In such cases, the generators only have to supply the residual load (the load which cannot be met by the renewable generation). However, at higher RE penetration, the requirement for frequency regulation and spinning reserves increases.

Often, inflexible base load generation cannot be cycled in large systems and power plants usually have a lower limit for generation output at which they can be operated safely (e.g. about 30% for diesel generators), making the role of electricity storage technologies important in systems with high RET penetration.

Geographic concentration of generation resources and lack of possibility for balancing over a larger area makes storage an important flexibility lever in small island and microgrid power systems. It becomes even more important when RE generation and demand profile are not complementary to each other. For example, demand in residential microgrids typically peaks in the evening while PV generation peaks in afternoon.

However, shifting of high penetrations of RE generation might not be economically viable at a system level in larger power systems (greater than a few MW) using electrochemical storage in the absence of pumped hydro storage due to high cost of storage and lower cost of fossil fuel generation [RES, UTI] (the biggest utility scale projects in the database are demonstration projects – a 4 MW/30 MWh NaS battery on Miyakojima Island in Japan and a 1 MW/7 MWh NaS battery on La Reunion).

Value creation: The main method by which value is created in this use case is by reducing RE curtailment and reducing expenses due to diesel consumption. This is done by shifting excess generation to times when demand exceeds RET generation, increasing the utilization of renewable power and reducing diesel consumption. Typically, RET time shift is combined with RET smoothing or area and frequency regulation in order to deal with short-term fluctuations in RE output.

Geographies: The use of battery technologies to integrate renewable power sources is fast becoming a viable option and activity is already being seen for replacement of existing diesel generation by renewables. Blechinger et al. [69] perform a global assessment of viability of renewable energy storage systems on small islands, finding them to be generally competitive with diesel-based generation, particularly in tropical and sub-tropical regions. Practically, there are several instances of projects in the Pacific (e.g. [70]), south east Asian countries such as Indonesia [60] and Malaysia [DEV], islands in the European Union with projects such as Tetiaroa in French Polynesia [TEC] and Graciosa in the Azores [TEC], and the Caribbean islands [TEC] – as well as for providing electricity access in microgrid projects for remote rural areas in Africa and India [DEV, RES].

A good example of large-scale battery installations is EDF’s (French utility Électricité de France) request for proposal (RFP) for 50 MWp solar PV and storage in 2012, which requires day-ahead predictions of constant power feed and ramp rates, with penalties for deviations over ±2.5%. In such cases, independent power producers (IPPs) need to have energy storage coupled with RE plants to avoid curtailment.

Ancillary Services (Area and frequency control, reserve capacity, RET smoothing)

Description: Frequency regulation is particularly valuable in small isolated power systems, which are characterized by low system inertia, resulting in high rates of change of frequency in response to power imbalances. When compared with interconnected systems, stricter technical requirements for grid codes and higher levels of reserves are required to maintain the same level of reliability and quality of service [68, DEV]. Several European island power systems have requirements to keep 30-40% of the generation capacity as reserves, in contrast with typical values of 15-20% in mainland interconnected power systems [61,71], resulting in conventional units running much below their rated power.

Increased shares of variable renewable energy sources can result in faster-declining frequency during large loss-of-supply events, resulting in a greater risk of lower frequencies that can lead to voluntary load shedding, machine damage, or even blackouts [72]. This further necessitates additional measures to be taken to maintain stability and reliability of the system due to decreased inertia and higher variability.

Value creation: The main source of value creation for this use case is increased dispatchability of RE and reduced requirement for reserve capacity from dispatchable generation. To control the ramp rate of wind generation, one can curtail the power output of the plant. The resulting energy losses can be as high as 18% [73]. Storage devices can be used to provide frequency regulation and reserves, allowing diesel generators to reduce fuel consumption by operating at a higher capacity factor and RE plants to maximize their output. However, the absence of markets puts the impetus on the utility to calculate the net benefit associated with the use of energy storage technologies in order to make an investment decision or to provide appropriate compensation to contractors [UTI, RES].

Table 3 Most relevant use case-specific risks identified through interviews

		Technology and Operational Risks	**Market and Counterparty Risks**
Mainland	**Demand charge reduction**	• Lifetime: Battery lifetime can be uncertain but some Li-ion battery manufacturers provide a 10-year guarantee to project developers for demand charge reduction and time-of-use tariff utilization [TEC, DEV]. Guarantees exclude combining further applications, and it is uncertain whether the additional benefits outweigh the reduced battery lifetime [DEV]. • Operational: Prediction of demand peaks is critical – missing one peak can result in loss of savings for entire billing period. The possibility of aggregation of projects with diverse demand profiles can have a portfolio effect, reducing the operational risk [DEV].	• Counterparty: The risk arises from insolvency of commercial counterparties, with which the contract is signed.
	Residential solar integration (Increase of self-consumption)	• Lifetime: Battery lifetime can be uncertain, but a 10 year guarantee for Li-ion batteries can be obtained for this use case • Operational: The risk of not generating value is low from an operational standpoint. Whenever a kWh of energy is not stored, the loss is only the otherwise saved electricity cost for this particular kWh. The possibility of aggregation of projects with diverse demand and solar irradiation profiles can have a portfolio effect, reducing the operational risk.	• Market: Reductions in electricity prices (due to reduction in the electricity tax or grid fees, for instance) can directly reduce the profitability of this use case. Also, with increasing deployment of distributed generation and thus self-generated energy, utilities come under pressure to increase the monthly or yearly fixed costs per connection in order to cover their costs in the future, which poses a threat to the profitability of this use case. • Counterparty: For a developed project, the revenue stems from the utility bill savings of the end-consumer. This makes household credit rating an important consideration for developers providing loans, and in third-party ownership models [DEV].
	Frequency regulation	• Lifetime: Battery lifetime can be uncertain but some technology providers offer a 20-year guarantee for frequency regulation projects in Germany [TEC].	• Market: Profitability based on historic prices is quite high, but market prices are difficult to predict. Opportunity costs depend on the mix of assets that provide the reserve [76,77], which is difficult to forecast over the project lifetime, especially because of the short development time for battery or demand response projects [76].
Island and microgrid	**Load following**	• Operational: The battery and control technologies are well understood and do not pose a significant technological risk for this use case [TEC].	• Market: A remuneration model based on savings as compared to the actual diesel price will be subject to volatilities in diesel price. The incidence of risk depends on how deal is structured (PPA/CAPEX/OPEX model).
	Renewable energy integration	• Lifetime: Remote areas and island nations often do not have the capability to design, operate and maintain hybrid power systems, which can increase operating costs and reduce project lifetime. Further, the effects of battery microcycling due to events such as transient cloud cover are still not fully understood [DEV].	• Counterparty: Off-takers such as utilities or consumers in the tourism [78] or mining sector [79] in the future [TEC] are the typical counterparties for these projects. In the case of rural mini-grids individual households or communities, the counterparty risk may be difficult to estimate.
	Ancillary Services (Frequency control and reserve capacity; RE output smoothing)	• Lifetime: Battery performance and effect on other components such as conventional generation resources in the system is not well-understood [UTI]. This is being studied through demonstration projects such as on Reunion [80] or on Miyako Island [75].	• Counterparty: Typically, the counterparty is the utility, whose credit quality influences the risk.

Geographies: Commercial deployment for this purpose is largely driven by regulations in places such as Hawaii and Puerto Rico [74]. The Hawaii Electric Company requires that wind turbines maintain their ramp rate below 1 to 2 MW/minute, depending on the time of day. Puerto Rico has similar constraints of ramp rate, with the additional requirement that the RE plant must have energy storage capable of providing ramp rate and frequency control. However, it was gathered from the interviews that while it is accepted that batteries can create value by serving this use case, the technical and economic performance of these technologies for this use case is not yet fully understood. Sigrist et al. [26] calculate the economic viability of providing primary reserve and peak shaving in the Canary Islands, finding that an IRR of 8% can be achieved using a 600 MWh/100 MW storage system on Gran Canaria. Further, island utilities are developing better understanding from the operational point of view through large-scale demonstration projects such as those in Reunion and Miyakojima [75].

4.2.3 Use case risks

While the previous sections have excluded risks for the six prevalent use cases, we summarize the most relevant risks specific to each use case in Table 3.

5 Conclusions

The present paper aims to serve as update and decision-making support for researchers, practitioners and policy makers by relating the applications for battery storage technologies reported in the literature with projects which are being pursued in different geographies. This has been done by (i) reviewing the literature on energy storage applications and profitability, and (ii) compiling and analyzing a database containing details about battery installations, as well as conducting expert interviews. The focus is on mainland and island/microgrid installations. To this end, six use cases, defined on the basis of conditionally viable applications or combinations of applications have been identified and described.

Certain trends emerge from the analysis. First, there is a large variation in battery storage projects today, in terms of the technology used, applications served and geographies. This indicates that the industry is still in an era of ferment, with no dominant design and significant variation, uncertainty and risks in technologies, markets and regulations – though it should be noted that this analysis is only a snapshot, and that major strides towards consolidation have been made in recent years. Dynamic tracking of activities in this sector would be useful, especially in light of the rapid developments taking place. Second, it is seen across use cases and geographies that policies play a central role in this process of consolidation, and in determining the viability of battery technologies. In fact, policies in the form of payments for services provided (such as FERC 755), grants (such as the SGIP and investment grants for demand charge reduction in New York and capital subsidies for batteries and solar PV in Germany and Japan), procurement and installation targets (such as those in California and Italy and off-grid electrification targets in Indonesia and India), minimum technical requirements (such as frequency control and ramp rate requirements in Hawaii and French overseas territories) benefit the majority of battery installations seen today. Finally, it is seen that battery storage projects can serve multiple applications, which can be combined to benefit from multiple revenue streams. The extent of combinability of the applications, operational strategies required to achieve it, business models and regulatory measures to facilitate these combinations, and quantification of their influence on the economic performance are some issues which need attention to enable battery technologies to fulfil this potential.

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7 Appendix

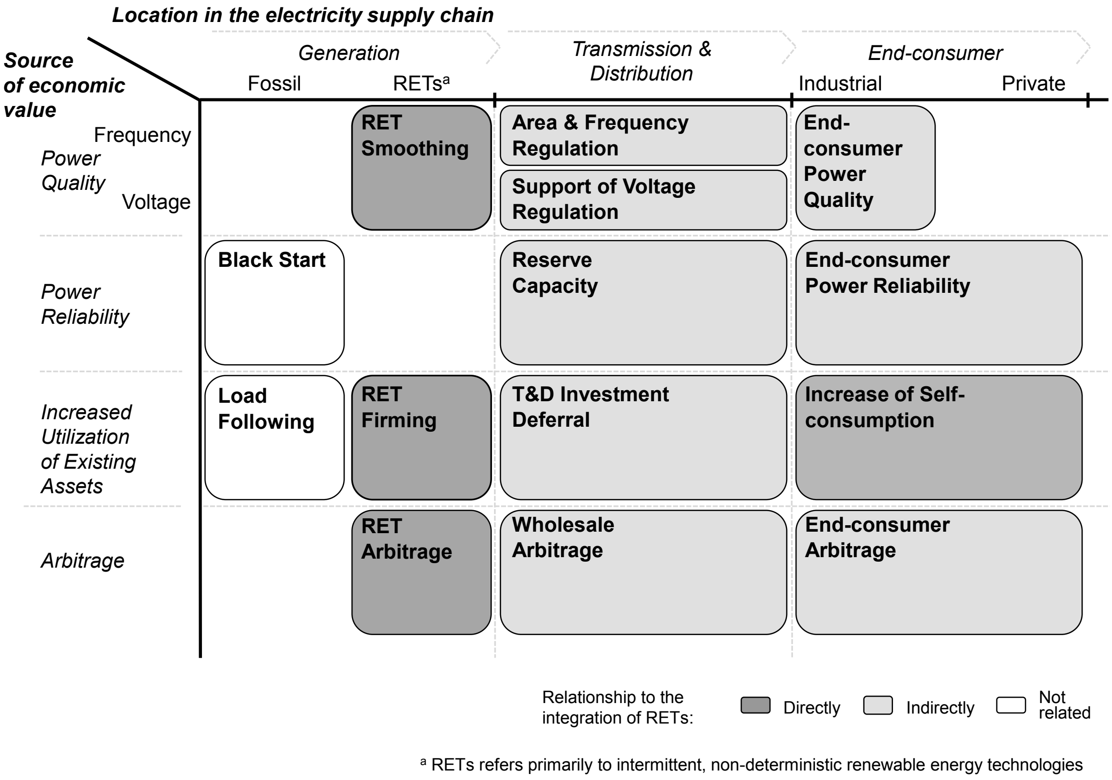

Figure A.1 Classification of stationary electric storage applications (taken from [21])

Table A.1 Description of energy storage applications

Source of Economic Value Creation	**Application**	**Description**
Power quality: These applications create economic value by keeping frequency and voltage levels within permissible limits	RET smoothing	Reduction of short-term variability of RET output.
	Area and frequency regulation	Maintaining grid frequency within permissible limits.
	Support of voltage regulation	Maintaining local voltage within a specified range by charging and discharging reactive power.
	End-consumer power quality	Conditioning power supply (frequency and voltage) for sensitive loads.
Power reliability: These applications create economic value by providing a source of back-up power in case of interruptions in power supply	Black start	Restarting a generation unit without relying on the grid.
	Reserve capacity	Balancing long-term imbalances in demand and supply (also known as non-spinning or minute reserve capacity).
	End-consumer power reliability	Providing uninterrupted power supply in case of power outages.
Increased utilization of existing assets: These applications create economic value by optimizing the use of existing assets in the power system	Load following	Maintaining the balance between electric supply and demand, while allowing conventional generation unit to operate at peak capacity.
	RET firming	Storing excess RET production to be used at a later time and increasing its dispatchability.
	T&D investment deferral	Deferral, reduction or avoidance of conventional grid investments by taking over technical functions in the electrical grid.
	Increase of self-consumption	Maximizing the self-consumption of energy produced by non-dispatchable distributed generation (e.g. solar photovoltaic).
Arbitrage: These applications create economic value by using price differentials over time, storing energy when prices are low and discharging when they are high	RET arbitrage	Storing energy produced by variable RET generators when prices are low to sell it when prices are high.
	Wholesale arbitrage	Buying and storing energy from power markets when prices are low to sell it when prices are high.
	End-consumer arbitrage	Making use of time-based pricing to reduce electric bills by storing energy when retail price is low and using it when the price is high, or by reducing peak demand.

Table A.2 Overview of expert interviews

Stakeholder	Code	Person	Interviewee
Technology provider	TEC	1	Chief technology officer of lithium ion battery manufacturer
		2	Senior scientist at power electronics and control system manufacturer
		3	Sales application engineer at zinc bromide redox flow battery manufacturer
		4	Director of strategic accounts at lead acid battery manufacturer
		5	Business development manager at redox flow battery manufacturer
		6	Chief strategy officer at iron chromium redox flow battery manufacturer
		7	Senior director at lithium ion battery manufacturer
		8	Regional sales manager at lithium ion battery manufacturer
Utility	UTI	1	Technical director for smart grids and island energy systems
		2	Head of grid operations at regional power company
		3	Energy storage specialist at regional electric power company
		4	Head of innovation management at international power company
Developer/ aggregator	DEV	1	Director of microgrid consulting and engineering company
		2	Managing director of microgrid developer and integrator company
		3	Development engineer at company providing energy solutions for telecom industry
		4	Technical manager at hybrid power facility developer
		5	Director of standalone hybrid power solution developer
		6	Senior vice president of sales at electricity storage aggregator
		7	President and CEO of electricity storage aggregator
		8	CEO of household energy storage developer and aggregator
		9	COO of household solar system developer
		10	CEO of household solar system developer
		11	Energy storage unit head at frequency regulation energy storage project developer
Research organization	RES	1	Research fellow at a non-profit policy and technology research organization
		2	Project manager for grid connected electricity storage at a public technological research organization
		3	Program officer at technology and policy support research organization

Table A.3 Energy storage application nomenclature

Source nomenclature	**Database nomenclature**
Grid-Connected Commercial (Reliability & Quality)	Power Quality - Consumer
Renewables Capacity Firming	Power Quality - Generation
Electric Supply Reserve Capacity - Spinning	Power Quality - Grid
Frequency Regulation	Power Quality - Grid
Load Following (Tertiary Balancing)	Increased Utilization - Generation
Voltage Support	Power Quality - Grid
Renewables Energy Time Shift	Arbitrage - Generation/Grid
Ramping	Power Quality - Generation
Electric Supply Reserve Capacity - Non-Spinning	Power Reliability - Grid
Black Start	Power Reliability - Generation
Electric Bill Management	Arbitrage - Consumer
Electric Supply Capacity	Increased Utilization - Generation
Distribution upgrade due to solar	Increased Utilization - Grid
Electric Energy Time Shift	Arbitrage - Generation/Grid
Onsite Renewable Generation Shifting	Increased Utilization - Generation
Transportable Transmission/Distribution Upgrade Deferral	Increased Utilization - Grid
Electric Bill Management with Renewables	Arbitrage - Consumer
Stationary Transmission/Distribution Upgrade Deferral	Increased Utilization - Grid
On-Site Power	Power Reliability - Consumer
Transmission Congestion Relief	Increased Utilization - Grid
Transmission Support	Increased Utilization - Grid
Transportation Services	Increased Utilization - Grid
Grid-Connected Residential (Reliability)	Power Reliability - Consumer
Transmission upgrades due to wind	Increased Utilization - Grid
Peak Shaving	Increased Utilization - Grid
Increased Utilization - Generation	Increased Utilization - Generation
Power Quality - Generation	Power Quality - Generation
Power Reliability - End Consumer	Power Reliability - Consumer
Load Leveling	Increased Utilization - Grid
Arbitrage - Generation	Arbitrage - Generation/Grid
Power Reliability - Generation	Power Reliability - Generation
Distribution upgrade due to wind	Increased Utilization - Grid