LOLABAT

"LOng LAsting BATtery"

H2020-LC-BAT-8-2020: Next-generation batteries for stationary energy storage

Grant Agreement n°963576

D2.4: Report on the compliancy and integrability of RNZB batteries for stationary applications

Lead Author: RINA-C
with contributions from: SuperGrid Institute, EDP and UNIGE
reviewer [Sunergy]

Deliverable nature	Report
Dissemination level	Public
Contractual delivery date	30/09/2021
Actual delivery date	13/10/2021
Version	Final

Release history

Release	Date	Author	Description
V0	21/09/2021	RINA-C	First draft
V1	29/09/2021	RINA-C	Final draft
V2	11/10/2021	SUNERGY	Review & slight modifications

Abstract

Context and Objectives

This document represents the fourth deliverable of WP2 "Specification of requirements, norms and standards for the next generation of stationary batteries" and is part of Task 2.3 "Assessment of the compliancy/integrability of NiZn batteries for stationary applications". The aim of this deliverable is to review the potential stationary energy storage applications for the Rechargeable Nickel-Zinc Battery (RNZB) and assess the technical performance characteristics required by battery systems to provide these services. A set of guidelines for the integration of the RNZB battery is then also provided.

Content

This deliverable contains a literature review of the main stationary energy storage services that are likely to be relevant to the future use of the RNZB technology. This literature review contains general details regarding each of the services, as well as technical specifications which highlight the requirements of battery systems to be considered suitable for use in each application or service. The services and applications are divided into three distinct sections of the literature review, these include Generation, Transport, and Consumers. Section 1.4 of this document assesses the performance of the RNZB and compares it to the required technical characteristics for each of the services reviewed. The suitability of the RNZB technology for each service is commented on, with any technical characteristics that fall the minimum threshold for each service being highlighted. Potential improvements to the RNZB are also considered in this section of the report.
Section 1.5 of this document contains the grid integration guidelines for the RNZB battery technology. First each level of RNZB integration is described with a bottom-up approach and a clear description of each component is given. Then an installation protocol is given where each step of the installation is described. Application of specific requirements are also given for each application segment.

Finally, the main conclusions of this report are provided in Section 1.6 of the document.

Attainment of the objectives and if applicable, explanation of deviations

The objectives of the deliverable and of the related task within LOLABAT project (T2.3) have been achieved as planned.

Glossary

Abbreviation	Description
AC	Alternating Current
aFRR	Automatic frequency restoration reserve
BESS	Battery Energy Storage System
BoP	Balance of Plant
BTM	Behind the Meter
C&I	Commercial and Industrial
DNO	Distribution Network Operator
DoD	Depth of discharge
DSM/DSR	Demand Side Management or Response
E/P	Energy to Power
EMC	Electromagnetic Compatibility
EMS	Energy Management System
ENTSO-E	European Network of Transmission System Operators for Electricity
EoL	End of Life
EOR	Extended Operating Range
ESS	Energy Storage System
EU	European Union
FCR	Frequency Containment Reserve
GIS	Gas Insulated System
GW/ GWh	Giga Watt/ Giga Watt hour
HV	High voltage
HVAC	Heating, Ventilation and Air Conditioning
ISO	Independent System Operator
kVA	Kilovolt-Ampere
LFP	Lithium iron phosphate
Li-ion	Lithium Iron
LV	Low Voltage
mFRR	Manual Frequency Restoration Reserve
MV	Medium voltage
MW/MWh	Mega Watt/ Mega Watt hour
NGESO	National Grid Electricity System Operator Limited
NMC	Nickel Manganese Cobalt
O&M	Operations and Maintenance
PCS	Power Conversion System
POC	Point of Connection
PPA	Power Purchase Agreement
PSP	Pumped Storage Plant
PV	Photovoltaic
RES	Renewable Energy Sources
RNZB	Rechargeable nickel-zinc battery

ROR	Run of River
RTE	Round Trip Efficiency
RTO	Regional Transmission Organisation
SF6	Sulfur Hexafluoride
SiC	Silicon Carbide
SoC	State of Charge
SoH	State of Health
STAR	Short – Term Active Response
STATCOM	Stationary synchronous compensator
T&D	Transmission and Distribution
ToU	Time of Use Cost Management
TSO	Transmission System Operator
UPS	Uninterruptable Power Supplies
ZNI CRE	French Tender of the Commission de la Régulation de l'Energie pour les Zones Non Interconnectées

Deliverable content

1.1 Introduction

Stationary battery energy storage systems can be used for a number of different applications and to provide a wide range of services. These services may be provided to the transmission system, distribution system, as well as behind the meter. Each of the services provided by battery energy storage systems has individual technical requirements, with desirable performance and price characteristics, that determine the suitability of particular battery technologies. With LOLABAT project focussing on the development of the new rechargeable nickel-zinc battery (RZNB), this document explores the current and projected future performance of this technology. It assesses its likely level of suitability for use in stationary applications and services. In the same fashion, a description of the main components used in most grid connected projects is presented along an installation guide that will open perspectives for the RNZB technology.

1.2 Objectives

This document aims:

- To provide a literature review of the potential stationary energy storage services that are relevant to the RNZB technology.
- To assess the requirements of the existing stationary energy storage services.
- To compare them to the performance characteristics of the RNZB technology. Then, the compliance of the RNZB technology with these applications will be assessed.
- To provide a set of installation protocols regarding the grid integration requirements and regulatory framework.

1.3 Literature review of energy storage services

This section aims to provide an overview of the different stationary energy storage services that the RNZB technology may be used to provide. Furthermore, the technical requirements applicable to battery energy storage solutions for each of these services are included in this section of the document. The energy storage services have been divided into three distinct sections based on the type of service. These sections are Generation, Transport, and Consumers.

1.3.1 Generation

1.3.1.1 Dispatchability for renewables (firming, ramp rate and time shifting)

Renewables have become one of the major contributors to clean electricity generation as well as one of the main drivers in Battery Energy Storage System (BESS). Amongst the many types of renewables at work, wind, hydro and solar have proven to be the most popular in electricity generation. Many of which are integrated with Li-ion batteries to provide storage. Both energy sources are intermittent and typically non – dispatchable, producing variable levels of energy that do not always align with required demand. Solar produces most of its useful energy during the day roughly matching the energy demand, however, the wind has less predictable speed intensity. Uneven generation from these sources poses a threat to grid operation that requires stability. Additionally, overcapacity of energy production from either source may result in adverse system impact. Energy storage is eminently suitable to adjust such imbalances and to smooth the variability of the system with the help of capacity firming, ramp control and energy time shift.

Capacity Firming

Renewable firming is an enabler of clean energy sources solving the issue that arises from the penetration of intermittent energy sources. There is a clear imbalance between the energy that is produced (from wind or solar) and delivered to the grid and the required demand. Firming helps to meet the required grid criteria for stability as well as maintaining a committed level of power for a given time, minimise costs, meet customer loads, promote renewable penetration, and avoid any disruptions in the system. This is particularly effective in islands that support weak grid supply, mainly in regions of Asia and Africa. In such cases, Capacity Firming enables remote areas or islands to have a consistent supply of electricity. Capacity firming at the utility-scale is likely to contribute 11% - 14% in battery (BESS) capacity in the future. [1]

The principal incentive lies in the day ahead production plan. Using the forecast of generation, grid constraints and BESS characteristics, a minute to hour plan is designed and sent to the grid operator. The Energy Management System (EMS) often generates the optimal day-ahead production plan as well as making sure that BESS can achieve the projected target, with a tolerance on installed capacity observed to be between 5% - 15%. If suppliers exceed the given tolerance, they may be subject to some form of penalty. This may be a payable fee, or the supplier is not paid until the balance is restored. In some cases, penalty calculations may lead to disputes between the operator and off-taker. Therefore, it is recommended that penalty calculations and billing is highlighted in documents and the operator and off-takers are made aware of this early on in the process.

Ramp Rate

Changes in grid stability and frequency variation can occur in grid systems that are easily affected by changing weather and variation in intermittent sources. Ramp rate introduces a faster and robust way to improve the false responses on frequency control and to improve stability. RINA’s experience shows that ramp rate control specifications require the plant combined power output to ramp up or down with predefined and/or scheduled rate limits. Depending on the ramp rate specifications complexity, the EMS may not be required to use advanced control strategy or forecasting tools, but RINA has established that it can help maximise revenues while extending BESS lifetime. Similar to Capacity Firming, failure to achieve these specifications can lead to either financial penalties or a period of unpaid injection.

Figure 1 below shows the operation of a 2.1MW/4.3MWh BESS collocated with photovoltaic (PV) with Ramp Rate Control Power Purchase Agreement (PPA) in Corsica. During Solar PV operation, the grid is required to supply a given power profile with the aid of storage. In this case, if the PV production varies from its forecasted values, the storage takes over to supply the difference. If the combined output power profile deviates too much from the firmed profile (typically 5%) a penalty is inferred for this loss (red). It should be noted that for the second case, some PPAs allow the operator to charge the BESS during the period of penalty to improve the injection profile following the penalty event.

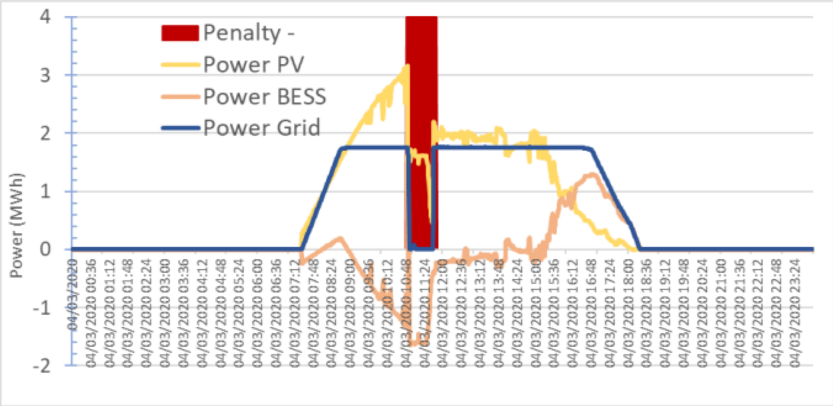

Figure 1: PV + BESS Ramp Rate Control and Peak Shaving [2]

Energy Time Shift

Like capacity firming, energy time shift involves the rescheduling of energy consumption and acts as a balancing mechanism. Energy consumption during peak hours is shifted to low peak periods where there is less demand and less activity. This is a cost-effective incentive brought in to benefit of the consumers. The Energy Storage System (ESS) is loaded with low–cost energy that is consumed when demand and energy prices are high during peak periods. The energy supplied during the peak period can either be used by consumers locally or traded directly on the wholesale market.

Figure 2 below shows a use case for an operation of a 3.5MW/4.5MWh BESS with PV with Energy Time Shift and Capacity Firming PPA on the island of Martinique. Power forecasted for the day ahead is highlighted Figure 2showing a clear indication of what the plant is supplying to the grid and what the tolerances of power injections are. The PV source can supply the power required for the grid demand, however if there is a shortfall in supply outside of the production plan, a penalty is applied for the supplier.

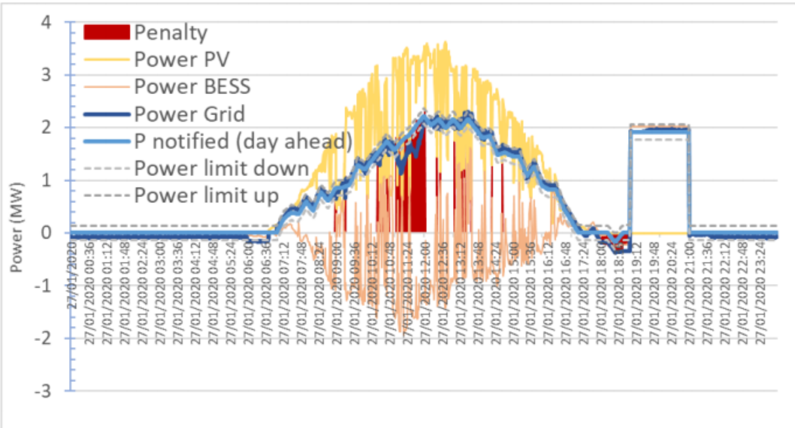

Figure 2: PV + BESS with Energy Time Shift and Capacity Firming [2]

Table 1 outlines the technical requirements for the RNZB battery to provide this ancillary service. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and state of charge. Additionally, stating the duration of the battery service required which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 1: Summary of dispatchability for renewables service technical requirements.

	Required value
Response time	1 – 5 seconds
Cycles[1]	>365 cycles/year
RTE	>90% @DC level
SoH EoL	70%
Duration	1h – 4h
C-Rate	0.25C – 1C
POC voltage[2]	MV or HV

The consistent, daily nature of these services results in a BESS being subjected to daily cycles, typically consisting of a full charge and discharge cycle. This usage profile highlights the importance of the cycling ability for any battery system that is intended to provide this service and can clearly be seen in the energy time shift example provided above (Figure 2). Furthermore, due to the day-ahead planning required in services such as energy time shifting, the response time of a BESS in this usage is not required to be as fast as other more dynamic services such as frequency response.

The duration of the BESS implemented is dependent on both the size of the renewable plant used, as well as the specific service being provided by the BESS. For energy time shift applications, the required BESS duration is likely to correspond to the length of the daily high demand periods in which it will discharge. For both grid firming and ramp rate applications the size of the battery will be dependent on case-specific parameters.

High round-trip-efficiency values are another key characteristic of BESSs that are aiming to provide dispatchability for renewables services. Maximising the amount of renewable energy that can be captured and subsequently released during key demand periods is key to driving the profitability of such installations.

1.3.1.2 Generator hybridisation (Hybridisation of power plant for extended operational range)

Short-term flexibility is a characteristic of generation resources that can be described along the following lines:

- **The activation time** which means how quickly a resource can deliver its rated power.
- **The technology scale** in MW indicates the energy scale at which the technology can participate in the balance of the electrical network.
- **The direction** indicates whether the generation resource is only consuming energy, producing energy or both.
- **Duration** indicates how long a response to the grid's needs can be maintained: a long duration requiring some kind of fuel, while a shorter duration may be based, for example, on storage.
- **The time shifting** means that a change in operating point must be compensated by an opposite action before or after, which is typical for storage. This characteristic therefore describes the independence or continuity of availability at different times. This means assessing whether the provision of flexibility during

[1] Defined as $Cycle\ life = \frac{\text{Lifetime throughput}}{\text{Nameplate capacity}}$

[2] This can be classified as High-voltage, Medium-voltage, Low-voltage, or given as an absolute voltage value.

one event affects the ability to respond to a later event. For example, the short-term flexibility provided by a battery is ranked low in terms of time shifting, whereas thermal plants generally have high independence and are therefore ranked high. It should be noted that there are cases where this can be sometimes the case and sometimes not: for example, in the case of Pumped Storage Plants (PSPs), it depends on the size of the reservoir and the inflow profile.

Hydropower is a source of flexibility with short activation times (<5min) and for large sizes: up to 1GW for the largest plants. Their operating ranges generally exceed 50% of their nominal power. For the last three criteria, namely direction, duration, and time shifting, we will find different specifications depending on the configuration of the hydro conversion plant.
Run of River (ROR) plants generally have very little (if any) capacity to modulate their power. However, some of them can do so: with a tidal range (even a small one) over a very large basin area, it is possible to adapt the production of a run-of-river plant to the day's cycle, which allows for short-term flexibility. Reducing generation by spilling is another, normally expensive, option. In addition, ROR plants can be more flexible by using forecasting, so they are able to adjust their generation in real time to the needs of the grid (assuming they have a small reservoir).

Storage hydropower refers to a hydropower plant with a reservoir that can keep the plant running for a period ranging from a few hours to several months. While plants with small reservoirs are typically used for diurnal variations (e.g., to generate during peak hours), plants with large reservoirs can also balance multi-day and seasonal variations, depending on the flow entering the reservoirs. In general, storage hydro is probably the most flexible form of large-scale power generation, with a power that often reaches 700 MW per unit. These plants will not have the capacity of ROR plants to work continuously, but because of their high flexibility they are intended to meet frequency and voltage control services. They can also fulfil the black start mission since they do not necessarily need an external energy source to restart and can provide the power and energy necessary for this kind of mission.

PSPs have an upper and a lower reservoir, and not necessarily an inflow (although with a zero inflow, evaporation losses must be compensated). During production, water is turbined from the upper reservoir to the lower reservoir, while during pumping, water is pumped from the lower reservoir to the upper reservoir. The typical efficiency of the cycle is 70-80%. Although it is arguably one of the easiest technologies to deploy, its application is severely limited due to geographic requirements. Like batteries, pumped hydro can provide short-term and varying degrees of flexibility depending on the basin size. It can provide services on the time scale of primary reserve (seconds) to intra-day periods (hours). Although the storage capacity of pumped storage is limited (e.g. 3 to 8 hours), it is significantly greater than that of batteries. Most pumped storage plants cannot regulate in pumped mode, they can only shut down, at least one pump at a time if there are multiple units. The only type of pumps that can regulate continuously are the so-called variable speed pumps, but they are relatively rare.

Table 2 shows a summary of characteristics of the three hybridisation power sources mentioned in previous lines.

Table 2. Summary of flexibility related characteristics for the three different sources for the hybridisation of power plant: i.e. run of river, storage hydropower and pumped storage plants

	Activation time	*Technology scale*	*Direction*	*Duration*	*Time-shifting*
Run of River	<5min	>20MW	↓	<15min	Weak: Any change in operating point must be later compensated by an opposite action
Storage hydropower	<5min	>20MW	↓	>2hours	Strong
Pumped Storage Plants	<5min	>20MW	↓↑	>2hours	Depends on the installation

It is understood that the hydropower asset is a very flexible tool at the grid level. It responds quickly, for a long time, with high power, and is generally able to freely adapt its operating point to the needs of the network. That being said, some limitations may arise:

- The operating range of a turbine is usually incomplete, i.e. it cannot operate continuously between 0 and 100% of its power; in the case of a multi-group plant this sometimes results in dead bands in the cumulative operating range of the groups. In addition, pumping is generally done at constant power.
- For conventional fixed speed topologies, ramping times are limited both by the inertia of the water masses in the pipes supplying the turbine with water, and by the performance of the actuators attached to the turbines. It sometimes appears that the performance of the actuators is degraded to increase the life of the system.
- In the absence of a pumping unit, it is impossible to store energy that would be abundantly available on the network.

In LOLABAT project, SuperGrid Institute will demonstrate the feasibility to extend the operating range of a PSP using RNZB. It aims at evaluating the opportunities to extend the services offered by an existing hydropower plant, designed to operate at fixed speed, upgraded with an energy storage system. This application called Extended Operating Range (EOR) enables an improvement of the operating range of a PSP in both turbine and pump mode, even if units are usually restricted in turbine mode and must pump at rated power only. In the next paragraph, two distinctive scenarios, where the EOR principle can be adapted, are depicted:

- The EOR of a single hydraulic turbine.
- The EOR of a PSP with several hydraulic turbines.

Figure 3 presents the dynamic strain of a hydraulic runner as a function of the output power (i.e. in a PSP the power output reflects the flow rate). As observed, it exhibits a non-convex shape which, for sustainability reasons, induces a dead band in the acceptable continuous operation region [1] [2] (orange section highlighted on the graph). Therefore, the custom continuous operation range of a conventional hydraulic runner is generally set to the upper part of the acceptable continuous operation range which can approximately cover [50%, 100%] of its maximal power or less. The goal of the EOR method is to fill in this dead band and to increase the operating range of the PSP. Thus, it unlocks a higher flexibility of a PSP.

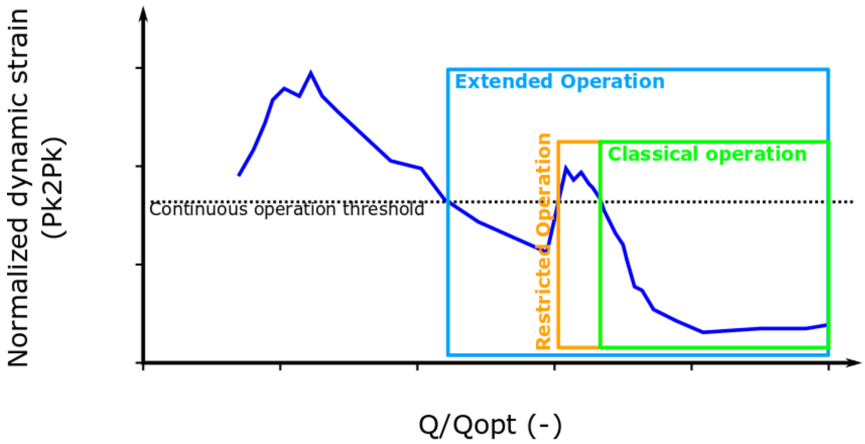

Figure 3: Dynamic strain limit the range of operation of a single hydraulic turbine

Note that this concept can be further applied to a PSP with multiple powerhouses. This also means that new innovative ways to optimise the operation of the plant can be demonstrated. Thus, the second scenario for demonstrating the EOR concept with the help of RNZB batteries would be to fill in the dead bands in the range of operation of a multi-group hydraulic power station.

Figure 4 illustrates the possible dead bands that can appear in the operation of PSP with 4 independent units. First, in Figure 4(a), the classical operation ranges of the plant are presented according to the state of the four units. Then, Figure 4(b) shows the possibility (in blue) to apply the EOR concept to propose new operating ranges. It should be noted that in the operating ranges highlighted in green, no EOR concept is applied. It corresponds to a combination of units either in pump or turbine mode with generally a hydraulic short circuit configuration. This latter intends to facilitate the simultaneous operation of several units, and thus participates also to increase the operating range. This configuration is considered for the continuation of the study. As it can be observed in Figure 4, three kinds of opportunities can be denoted for EOR application:

- EOR in turbine mode: It consists in covering dead bands in turbine mode, when it is required to switch between N and N+1 active groups.
- Full EOR: It consists in covering all the full height of the dead band in pumping operation. Note that it would require a high-power capacity.
- Partial EOR: It covers partially pumping operations, and potentially allow a better technical and economic trade off since lower energy and power capacity are required.

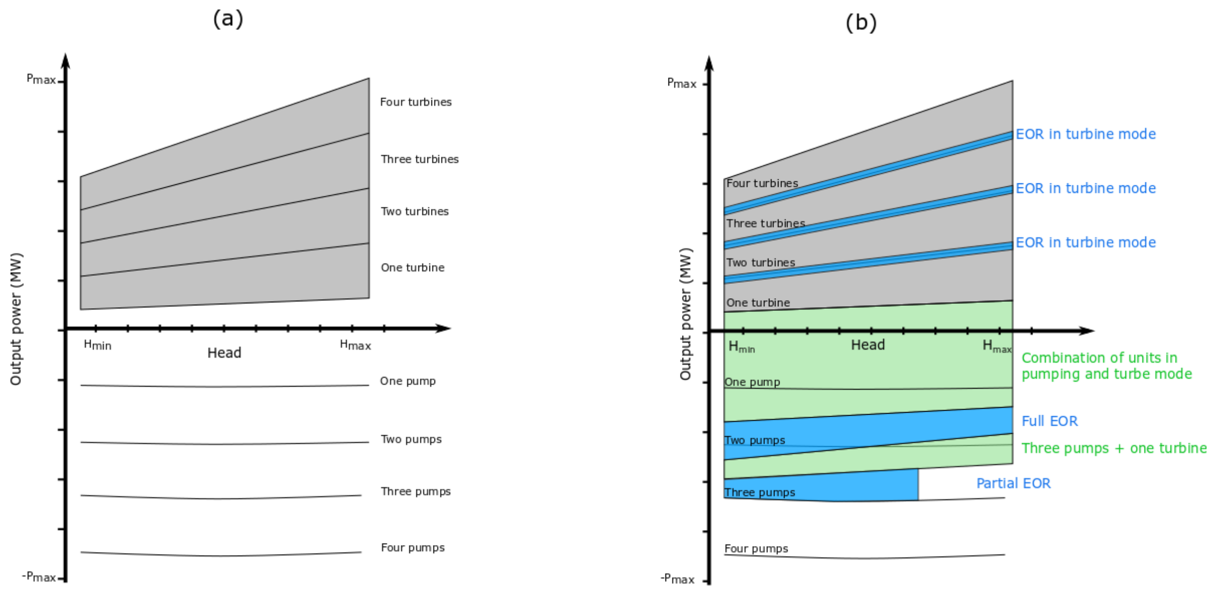

Figure 4: Range of operation of a multiple group pump storage plant with: (a) A conventional plant (b) The opportunities for the EOR concept with RNZB batteries to upgrade a conventional plant. Note that the head refers to the net pressure applied to the plant with respect to the filing of the upstream and downstream reservoirs.

Finally, Figure 5 describes the working principle of the EOR concept with RNZB stationary storage technology. It consists in dynamically switching the power output of the hydraulic turbine(s) (in blue) between two set points around a dead band (in red). This band corresponds to a harsh operation zone, which must be avoided. However, the goal is to be able to propose this operating point from transmission system operator (TSO) point of view. Therefore, the electrical production (in green) is smoothed out with batteries (in orange) to fulfil a given set point (black dashed line) inside the dead band.

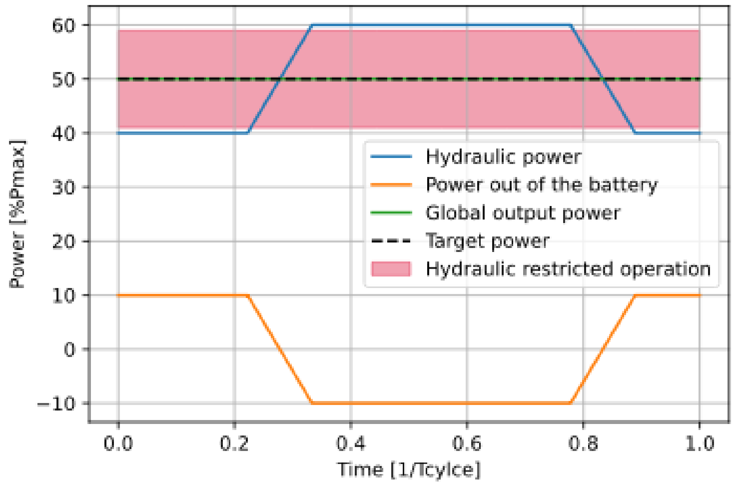

Figure 5: Working operation principle of the EOR concept applied to a single hydraulic turbine.

Table 3 outlines the technical requirements required for the RNZB battery in order to provide the ancillary services. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and state of charge. Additionally, stating the duration of the battery required which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 3: Summary of generator hybridisation service technical requirements

	Required value
Response time	Milliseconds to seconds
Cycles	1 cycle per day
RTE	>80%
SoH EoL	70%
Duration	0.5h-1h
C-Rate	<1C
POC voltage	MV-HV

1.3.1.3 Whole-sale market arbitrage

To meet the future energy supply and demand, it is crucial for the energy market to take a more dynamic approach on the pattern of generation and consumption. Currently, renewable energy sources such as solar and wind are only able to generate a fraction of their capacity, some of this excess energy generated is lost and a non-renewable generation is required to meet sudden peak demands. Energy storage offers solutions for which it is highly capable in meeting the flexible nature of today's electricity demand and balancing the variation in the grid system. Under wholesale market arbitrage, BESS stores power during off-peak periods when it is cheap, generally this time periods are at night. BESS then discharges this energy so it can be sold and distributed during peak demand or when it is the most economic to do so. It is one of the simplest concepts of BESS for technical and commercial purposes. The diversification of battery technology in the current market means that demand can be met under a range of potential flexibilities and availability.

A benefit of power arbitrage is load demand curve shifting to alleviate the stress of high demand during peak times. By distributing excess energy during peak demand, high energy tariffs can be avoided for consumers. Peak and off-peak periods in most consumer cases such as residential and commercial are predictable making the dispatch of electricity for the TSO easier. Figure 6 below shows the behaviour of BESS during a 23-hour period. Between 10AM and 4PM, renewable generation is at its highest with lowest consumer demand. A BESS will be able to absorb energy during this period to relieve the pressure during peak demand between 5PM to 10PM. This is a time when energy prices are at their highest and it is a financial incentive for the sellers to sell their stored energy [2].

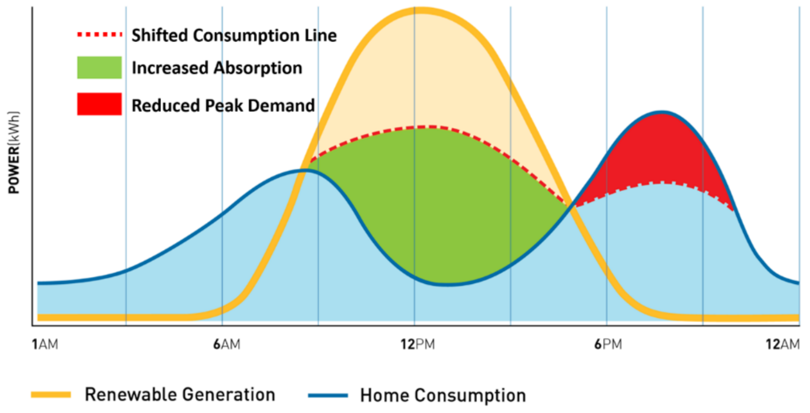

Figure 6: Concept of power arbitrage via renewable generation.

A study from commercialization of energy storage in the European Union (EU) found that there is a lack of regulatory acknowledgement of storage [3]. The low consideration and lack of clarity of rules have produced obstacles for a full integration of the storage into the market. The TSOs and Distribution Network Operators (DNOs) are unable to own and operate storage or to purchase a Transmission and Distribution (T&D) deferral in some of the European countries (Germany, France, Spain and Greece) with minimal access to the ancillary market [4]. Contrary to this, Great Britain and Italy have integrated their TSO/DNO to operate storage and have control of transmission and distribution deferral. An EU country that is currently at the forefront of most developed governing for storage is Germany. On a more global scale, California in the US is considered the front runner for storage regulation and deployment. Time shift application in storage technologies for wholesale market participation is allowed in France, UK, Italy, Spain, Greece, and Germany. Although, some countries (France, Italy, Spain, and Greece) have regulations that only allow pumped hydro to participate in the frequency reserve market [5].

Table 4 outlines the technical requirements required for the RNZB battery in order to provide the ancillary services. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and state of charge. Additionally, stating the duration of the battery service required which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 4: Summary of whole-sale market arbitrage service technical requirements.

	Required value
Response time	1 to 5 seconds
Cycles	>365 cycles/year
RTE	>90%
SoH EoL	>80% (desirable)
Duration	1h to 4h
C-Rate	0.25C to 1.0C
POC voltage	MV and HV

A key technical characteristic of a BESS planned for use in arbitrage services is the round-trip efficiency (RTE) value of the system. An important principle behind arbitrage is charging the BESS during periods of excess generation when the price of energy is low, before discharging the system during periods of high demand where

the price of energy is higher. Being able to maximise the amount of energy that can be discharged during these periods of high demand is paramount to the potential profit that can be made using this service. In a similar fashion, the number of potential charge and discharge cycles that can be completed by the BESS is another key attribute that impacts the financial viability of such a project. In order to maximise the lifespan of the battery system and to reduce system stress, both the charging and discharging of the battery are typically slow. It is unlikely that the charge or discharge C-rate of the BESS will be greater than 1.0C during the provision of this service.
Due to the range of different markets and market conditions that such a service can be operated within, there is a significant degree of optimisation involved in deciding when to charge and discharge the BESS, as well as for how long these cycles are to last. This results in a wide range of potential battery durations being utilised, with this value being optimised based on case-specific costs and use case methodologies.

Due to the daily nature of both high and low demand periods, a BESS utilised to provide arbitrage services is likely to complete a minimum of one charge and discharge cycle per 24-hour period. Similarly, due to the planned nature of both charge and discharge cycles (with this service typically being acquired via day-ahead markets) the response time is a less critical technical characteristic in the provision of this service.

1.3.1.4 Mini-grids

Mini-grids are small-scale electricity grids, providing power in the range from 10kW to a few MW. Micro-grids have similar features compared to mini-grids, being both decentralised grids connected to a limited number of local users. However, micro-grids are smaller in size with maximum power output of 10kW [6]. Mini-grids can operate in two different configurations: *parallel* or *islanded mode* [7]. The advantages of one mode compared to the other depend on different factors such as location of the consumers, availability of resources and economic scenario.
Under parallel (or on-grid) operation, the mini-grid is connected to the primary central grid, allowing electricity imports and exports according to the specific needs of the grids. This configuration can provide several benefits to both the mini and primary grid: the mini-grid can sell energy and provide ancillary services to the main grid, but at the same time the connection to the main grid allows for more reliable energy delivery to the local end-users. ESSs have a fundamental role in ensuring that mini-grid can provide different services to their consumers, especially if a considerable part of renewable generators is present. In particular, battery storage systems can smooth, firm or shift the intermittent and non-dispatchable renewable generation. In addition, batteries can also be used in synergy with fossil fuel engines to improve their efficiency and lower the carbon footprint of the plant. As a consequence, electrochemical storage systems have a great potential for increasing the utilisation of local resources and reduce transportation losses, reducing import and export with the main grid.
Under *islanded* (or o*ff*-grid) operation, the mini-grid does not rely on the connection with the primary grid. The typical end users of islanded mini-grid are remote communities or islands, where the connection to the national grid is unfeasible from economical and practical perspectives. In this configuration, batteries have the important role of contributing to the provision of secure energy to the local users by maintaining the frequency and voltage stability through regulation of the real and reactive power output.

Electrochemical storage systems have already proven to be key in enabling significant reductions in electricity costs and fossil fuel utilisation, as well as improving the reliability of the electricity supplied to the consumers. An example is the mini-grid operated by Hitachi ABB Power Grids in Johannesburg, South Africa, used in their Longmeadow facility to power the factory and offices. The system main components are constituted by a solar PV system, providing 10 kW during peak production, two 600kW diesel generators as backup systems and a battery-package of 1 MW/380 kWh [8]. In this configuration, the battery is used for peak shaving, to maximise the use of the solar panels and to limit the diesel engines operation. In addition, the battery is used to ensure frequency and voltage stability and allows for operation in both grid-connected and islanded mode as well as supporting the transition between the two modes.

An example of mini-grid operated only in island mode is the one of the Kodiak Island of Alaska. The initial island system included 4.5MW of wind power, 23MW hydropower and 33MW diesel engines power capacity [9]. Subsequently, a 3MW/750 kWh battery was integrated to allow the installation of an additional 4.5 MW wind power capacity in the grid to further increase the renewable share. This was done because the battery can ensure frequency stability despite the intermittency of the renewable sources. This obtained several benefits, such as the reduction of curtailment of renewable energy and fossil fuel consumption since diesel engines do not have to be extensively employed to absorb frequency fluctuations. As a result, the Kodiak Island is able to achieve over 99% of their power production from renewable energy sources (RES).

A case study of mini-grid operated in parallel with the main grid is represented by the system developed at the village of Feldheim, in Germany, which consists of several renewable energy sources (solar, wind and biogas) and an electrochemical storage system [10]. The total annual output by the solar panels is around 2700MWh, with the biogas plant providing around 4GWh and the wind farm providing 81MW. The 10MW/10.7 MWh battery storage is used to provide ancillary services by absorbing grid unbalances and to help to regulate the frequency of the national grid [11]. As a result of the local renewable exploitation and the ancillary services provided to the main grid, the electricity costs dropped over 30%.

Table 5 outlines the technical requirements for the RNZB battery to provide this ancillary service. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and state of charge. Additionally, stating the duration of the battery required, which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 5: Summary of mini-grid services technical requirements.

	Required value
Response time	100ms to 5s
Cycles	2000-4000
RTE	>80%
SoH EoL	60%-70%
Duration	2h-4h
C-Rate	<0.5C
POC voltage	LV-MV

The technical requirements for a BESS that is planned for use within a mini-grid depends significantly on the specific use case and implementation. In the examples above, the use case of renewables dispatchability is highlighted. It is worth noting that certain requirements may be altered to fit the exact use case of the BESS within a mini-grid. This may include items such as the requirements for the BESS to have an increased duration to provide a level of safety for mini-grids being operated in island mode.

1.3.2 Transport

1.3.2.1 Frequency Response

Modern interlinked power systems request efficient and reliable frequency response mechanisms. To ensure a stable grid frequency, the system operators need to constantly monitor and act in response of frequency reference

value experience deviations. The mechanisms applicable are available through balancing services, based on reactive short-term response to level out frequency deviations in the power grid.
Frequency deviations, e.g., following a power generation outage, will be tackled by the automatic intervention of Frequency Containment Reserve (FCR), that will target the restoration of the balance between supply and demand in the entire synchronous area. FCR is also known as the primary reserve. The FCR, that is also known as primary control reserve, is the first response to frequency disturbances. Primary reserve aims to automatically correct small deviations between generation and consumption and all generators are required to participate. Typically, the reservation of this service is paid, whilst the activation of the service is not. Energy storage is suitable to contribute and assist other FCR mechanisms maintaining balance between generation and consumption within a synchronous area.

If the deviation persists, the automatic Frequency Restoration Reserve (aFRR) subsequently replaces the primary control reserve. The aFRR, also known as secondary reserve, can be considered as a second layer reserve, that assists system operators on grid frequency stabilisation and that can also be activated through balancing services, from balancing service providers.
Secondary reserve replaces FCR gradually, after a few seconds, before the tertiary reserve, supports or partially substitutes aFRR, after some minutes. Energy storage can also contribute to adjust the active power output, restoring desirable frequency levels back after the primary control stopped frequency excursions. Secondary reserve's purpose is to correct deviations from dispatch programmes. All generators, except for non-manageable resources participate and both, capacity and energy are remunerated. Capacity is paid according to the marginal price and the energy used is paid according to the price that would be paid if tertiary reserve has been used instead.

Tertiary reserve is usually activated manually by the system operator in case a sustained activation of the secondary reserve is expected. Thus, it is primarily used to free up the secondary reserve in a balanced system situation, but it is also activated as a supplement, after larger incidents to restore the system frequency and consequently free the system wide activated primary reserve. Tertiary reserve is also referred to as manual Frequency Restoration Reserve (mFRR).

Energy storage might be used to restore the primary and secondary reserves and bring the frequency and interchanges back to their target values when the secondary reserve is unable to do it.

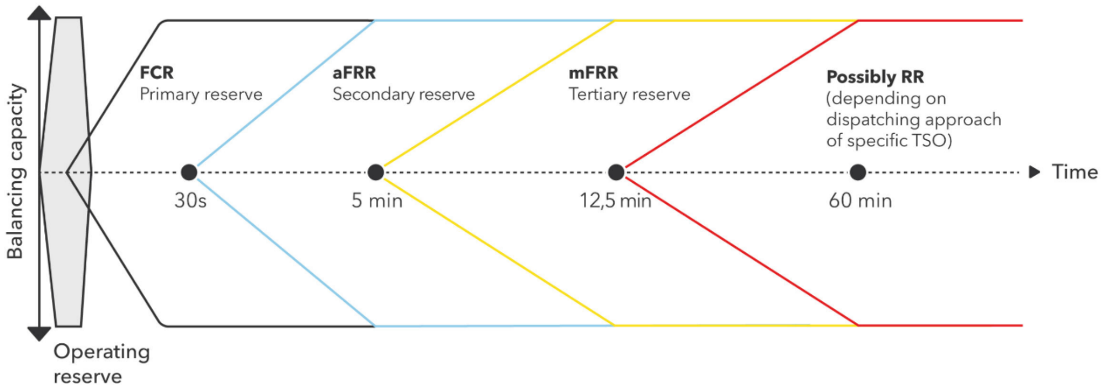

Figure 7: When and how the different frequency reserves are activated.

As FCR reacts to short-term frequency imbalances, the complete activation of the frequency primary reserve must be available within 30 seconds and cover a period of 15 minutes per incident, according to the ENTSO-E [12] standards.

Therefore, the system operator must activate aFRR after 30 seconds and if the imbalance persists after 12.5 minutes, the manual Frequency Restoration Reserve (mFRR) supports or replaces the secondary reserve gradually (see Figure 7). All generators, except for non-manageable resources participate. Only energy is remunerated, based on the marginal price of tertiary reserve, that is calculated from the offers made for that specific service.

The users of the balancing services described are the system operators.

Generally, reserve based balancing services are required by system operators across Europe, with some being of mandatory provision. The products and remunerations schemes may vary, but many different European countries require these balancing services, e.g., Belgium, France, Germany, Great Britain, Italy, Netherlands, Poland, Romania, Spain and Switzerland, as well as at clusters level, e.g., the Balkans, all the Baltics, central and eastern Europe – Czech Republic, Slovakia, Austria and Hungary –, islands – Iceland, Malta and Cyprus –, all the Nordics and western-like, such as Luxembourg, Greece, Ireland and Portugal [13].

Services such as enhanced frequency response and frequency containment reserve have been developed to provide frequency response in 1 second or less [14]. These services aim to facilitate shorter control cycles. For both enhanced frequency response and frequency containment reserve, the size of solutions typically range between 1 to 50 MW installations, also depending on the generation units' size, with an approximate 1-1.5h energy-to-power (E/P) ratio achieved by pooling smaller units. High to very high-power dynamics and relatively small energy throughput (~1 cycle per day) are required.

For frequency restoration reserve, typically 10 to 1,000 MW with E/P ratios > 5h, will be achieved by pooling of smaller units. Moderate power requirements and energy throughput are required, strongly depending on the composition of the electricity supply system and demand variations, market design and other soft factors, e.g., weather forecasts accuracy and demand-side management potential [1].

Table 6 outlines the technical requirements for the RNZB battery to provide the Frequency Response service. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health at end of life and state of charge. Additionally, stating the duration of the battery required which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing service to High/Medium/Low voltage connections.

Table 6: Summary of frequency response service technical requirements.

	Required value
Response time	15 – 30 seconds (primary) 30 – 100 seconds (secondary) 5 – 15 minutes (tertiary)
Cycles	Continuous >365 cycles/year at 80% deep of discharge (desirable), frequency response Minimum cycles/year, 10 – 50, operating capacity
RTE	>90% (desirable)
SoH EoL	80% (desirable)
Duration	15 seconds up to 15 minutes (primary) 30 seconds up to 15 minutes (secondary) 5 minutes up to 2 hours (tertiary)
C-Rate	0.3C – 1.5C
POC voltage	MV or HV

The ideal characteristics of a BESS for use in frequency response vary greatly depending on the specific service type (primary, secondary, tertiary, or a combination) that it is planning to provide. Both the response time and required duration are significantly impacted by the service being provided, with primary response initiating faster and lasting for only a short period of time compared to the relatively slow response and long operating time of the tertiary response. Furthermore, the service being provided will also dictate the required C-rate of the battery system, with primary response favouring higher C-rates due to the shorter operation period. Due to the range of required performance characteristics, many different battery energy storage technologies are able to be considered suitable for use in frequency response services, as different performance characteristics influence the technology's suitability for each of the frequency response services. As is the case for all BESS services, the RTE is important to maximise the profitability of the project.

1.3.2.2 Operating reserves

The operating reserve is surplus operating capacity that can instantly respond to a sudden increase in the electric load or a sudden decrease in generation, e.g., due to renewable power output decrease. Operating reserve provides a safety margin that helps to ensure reliable electricity supply despite variability in the electric load and volatility in renewable power supply.

Energy storage can be used to replace and restore required primary and secondary reserves that must be prepared for further system imbalances. Within this operational context, energy-storage based operating reserve may face activation times from time-to-restore frequency up to a few hours.

Following an event of loss of generation or loss of an import source, provided by an interconnection, leading to a mismatch between supply and demand, operating reserve must be activated. Operating reserve can be provided by the reduction in demand, known as demand response, which must be realisable in real-time operation to respond and contain any system frequency fall, correcting it to an acceptable level. Additional output from active power generation units is another form of providing operating reserve. Larger power stations can contribute and provide spinning reserve, which is a more common term for operating reserve. Operating reserve is also used because batteries and fuel cells can provide it as well, but they do not spin.

Modern power systems must always provide some amount of operating reserve because the electric load tends to fluctuate randomly, and in systems integrating higher share of renewables, such as wind and solar, additional operating reserve is required to safeguard system's stability against renewables' power supply intermittency.

The operating reserve should be equal to the operating capacity minus the electric load. Regarding the operating reserve provided by batteries, e.g., if the storage system is discharging 2kW but can discharge 10kW, then it can provide 8 kW of operating reserve, depending on inverters' efficiency. So, the storage can supply an alternating current (AC) load even if the load suddenly increases as much as 8kW.

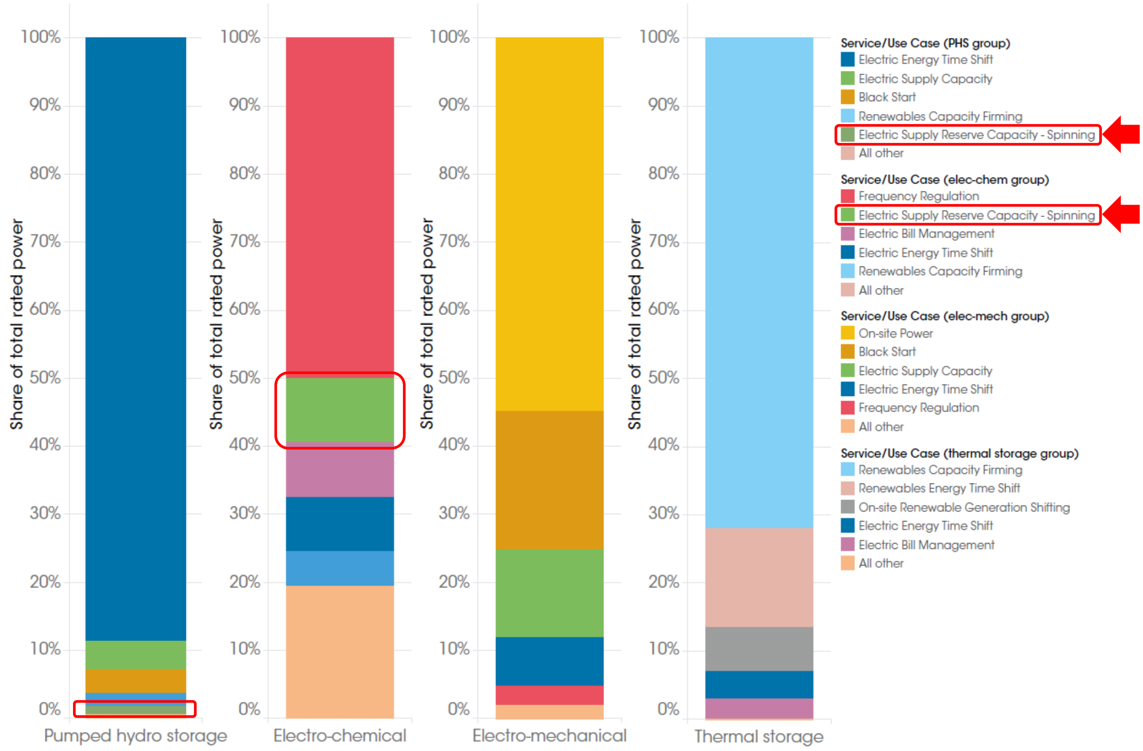

Figure 8: Global energy storage power capacity shares by application and technology [15]

Globally, operating capacity is provided by different storage technologies, with a share of less than 1.5% of total pumped hydro storage rated power being used for this purpose and nearly 10% of all the electro-chemical storage capacity being used as operating capacity.

The share of total electro-chemical rated power used for frequency regulation is significative (see Figure 8, electrochemical bar, red area), more than 50%, highlighting the potential of battery-based energy storage systems to participate in ancillary services and to support transmission and distribution infrastructures.

The users of the operating capacity available are the system operators, responsible for maintaining system's stability and act to prepare the system for incoming disturbances by replacing and restoring FCR and aFRR. Operating capacity power requirements and energy throughput strongly depend on the composition of the electricity supply system and demand variations, market design and regulation. Different remuneration mechanisms can be applied, that might be separate capacity payments for availability and investment or an energy-only market with additional strategic reserves safeguarded or a centrally procured capacity auction ahead of the delivery date.

Table 7 outlines the technical requirements for the RNZB battery to provide this ancillary service. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and state of charge. Additionally, it states the duration of the battery required which is subject to change, depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 7: Summary of operating reserve service technical requirements.

	Required value
Response time	1ms to 500ms
Cycles	1500 - 3000
RTE	>75%

SoH EoL	70%
Duration	15 minutes to 2+ hours
C-Rate	0.5C - 4C
POC voltage	MV and HV

The required duration of the battery system is dependent on the exact operating reserve service that it is planning to provide. For example, the UK National Grid Fast Reserve service [16] includes a minimum requirement of 15 minutes of reserve energy, whilst their Short-Term Operation Reserve service requires a minimum sustained response of 2 hours. Specific power requirements are also present for both of these services, with the Fast Reserve service requiring a minimum of 25MW delivery (at a delivery rate in excess of 25MW/minute) and the Short-Term Operating Reserve requiring a minimum of 3MW of generation [17]. The ideal BESS technical characteristics for this service are likely to vary significantly depending on the specific market it is planned to participate in. Optimisation of the plant size, duration and cycle life are likely to depend on the optimisation based on specific renumeration details, market design and demand details.

1.3.2.3 Voltage support

Voltage support is a reliability service provided by energy storage to maintain voltages within acceptable ranges between the ends of each transmission line. It is essential for the optimal operation in all equipment, prevents overheating damage to generators and aids in reducing losses. The system requires a regulation for voltage over a wide range of load conditions.

Initially, the grid power system uses transformers to achieve a balance in voltage via tap chargers, in-line voltage regulators and Static Var Compensator (SVC). However, these only provide step voltage changes with limited response. A more dynamic approach to voltage regulation comes from STATCOM. These can provide a more robust solution for the grid stability by providing reactive power (kVA). Absorption of reactive power helps to maintain voltage level in the system and on the grid [18].

Unlike frequency system that is consistent across the power network, voltage changes are experienced at points across the lines depending on the level of real and reactive power[3] of the loads as well as power factor which can also result in lower voltages. STATCOMs are useful in injecting reactive power near the loads. This enables the reactive power to be absorbed to maintain voltage levels across the transmission lines avoiding any form of loss. Additionally, the injection of reactive power also minimises the varying load conditions in the power system. An inverter connected to BESS can also act as a STATCOM. In this case, BESS can provide and absorb the amount of reactive power needed to aid with voltage regulation, but also provide active power for Frequency Response, improving thus the range of functionalities of a traditional STATCOM.

Voltage Regulation is observed to be available on every BESS deployed in the last 10 years. Some of these locations include parts of Europe such as Corsica, regions in Africa, Asia, US, UK, and Australia. There can be issues where the system lacks the amount of active power both on import and export than the required rated amount. A solution would be to design a robust power system in a way that is able to supply both active and reactive power throughout.

Table 8 outlines the technical requirements required for the RNZB battery in order to provide the ancillary services. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and

[3] Active power is the real electrical resistance power consumption in a circuit, whilst reactive power is the imaginary inductive and capacitive power consumption in a circuit.

state of charge. Additionally, stating the duration of the battery required which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 8: Summary of voltage support service technical requirements.

	Required value
Response time	1ms to 2000ms
Cycles	1000 - 2000
RTE	NA
SoH EoL	>70%
Duration	0.5 to 1 hour
C-Rate	NA
POC voltage	MV and HV

One of the principal benefits of battery STATCOMs is the ability to respond rapidly to changing system conditions (since they have no mechanical inertia) [19]. As a result, it is important that batteries planned for use in voltage support applications be able to meet this demand for fast response times. Due to the use of the battery for reactive power control in this application, during the provision of this service energy is not 'consumed' from the battery. This results in a lowered requirement for the cycling ability of a battery that is to be used for this service. It is also worth noting that this service is typically a mandatory service for grid connected projects (grid code dependent).

1.3.2.4 Black start

In a fast-moving service such as power generation and distribution, it is inevitable that disruptions are likely to occur. These can be disguised as partial power cuts and total blackouts which in hindsight need to be planned for to avoid disruption of good service. Energy companies or independent system operators (ISOs) such as National Grid in the UK are the key players that plan for such delays using Black Start.

Black-start services are designed to help restore energy back on to the grid after a total or partial shutdown. It is a process in which the power is brought back online in plants/grids without using the transmission network for support, something that has usually been achieved by designated diesel generators. In the event of a black start situation, the process entails isolated power stations to start back individually and then eventually being connected as a complete system. By contrast, BESS has started to play a useful role in this. Energy storage is important in this aspect because it has the advantage of storing energy that might be wasted otherwise and instead provide a fast response on a short-term time scale. If a substation is affected by the transmission or distribution outage, energy storage can provide the required backup support by sending start up power to generators to achieve synchronisation. An integrated Power Conversion System (PCS) would also be beneficial in providing grid forming capabilities and a frequency reference. After synchronisation is achieved, BESS absorbs energy produced by the plant until customers are brought back online. Some areas where this might be most beneficial are countries that are likely to suffer from black out during bad weather or seasonal changes such as extreme heat e.g., states in US, parts of Asia and Australia.

Use case: Siemens recently announced in 2021, that it will design its first black start battery storage system at Clearway's 720 MW Marsh Landing Generating Station in California. They are said to engineer a BESS system that can support three attempts to restart a unit within one hour [20]. A new system is set to be implemented with transformers to increase voltage, switch gear that will aid the integration of BESS with the Marsh Landing system, electrical, civil, control and structural engineering. BESS empowered solution for black start will provide a quick start, lower emissions, and improve grid reliability.

Table 9 outlines the technical requirements for the RNZB battery to provide this ancillary service. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and state of charge. Additionally, stating the duration of the battery required which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 9: Summary of black start service technical requirements.

	Required value
Response time	1ms to 1000ms (within an instruction timeframe, e.g. 2 hours for the UK National Grid service)
Cycles	Low number of cycles due to the infrequent nature of this service
RTE	>75%
SoH EoL	80%
Duration	The ability to provide multiple black starts is likely due to possible tripping during the re-instatement period. E.g. UK National Grid requires the ability to provide at least 3 black starts.
C-Rate	UK National Grid requires the capability to accept instantaneous loading of demand blocks in the range of 35MW to 50 MW
POC voltage	MV or HV

The Black Start use case highlights a number of specific technical requirements for battery energy storage systems. A high service availability is required due to the unplanned events which are likely to lead to the need for the Black Start service to be provided. Typically, a 90% service availability is requested. The ability to self-start is another key requirement for the Black Start service.

The connection voltage for a BESS providing Black Start services is likely to be either medium or high voltage (with a capability of at least 100 MVAr leading reactive power typically requested by UK National Grid Electricity System Operator Limited (NGESO)), with BESSs connections typically being targeted at the distribution grid level in this case. Furthermore, the BESS will be required to be able to accept instantaneous loading of demand blocks in the range of 35MW to 50MW in order to meet grid restoration needs. The ability to provide multiple black starts is also required; this allows for any potential tripping that may occur during station starting sequences or in the transmission and network distribution systems during the reinstatement periods. NGESO requires the capability to provide at least three sequential Black Starts [21];

1.3.2.5 Transmission and distribution upgrade deferral and congestion relief

The demand for electricity is on the increase. It is not a surprise that with major economic growth in cities and urban development there is access load growth and rising peak demand that can usually end up causing congestion in the grid. This congestion can be seen as build up current in transmission line, potentially leading to a failure or reduced lifespan for equipment such as switches, transformers, and cables. In certain cases when a congestion on future transmission lines has been predicted by software testing, the first solution is to increase the size of the conductor to reduce the losses through the lines, thus decreasing the current strain and congestion build up. The requirement for constant increase in conductors and other equipment can be a financial concern as maintenance for equipment is likely to increase thus the cost to replace them. To avoid continuous equipment enhancements in the grid system and overcome traffic jam in the transmission and distribution lines, a solution would be to provide a deferral system that would upgrade sections of transmission and distribution (T&D) network. T&D upgrade deferral allows for better management of load carrying capacity of the equipment and possibly extend the life of it. Energy Storage Systems emerge as the ideal players in this. Some of the benefits of ESS is to be able to store and provide energy for systems that are in situations where demand is high, but provision constrained [22].

The BESS/ESS will have to be electrically located downstream from the required equipment and location of aid. BESS will not be required to operate for short number of hours, specifically when the demand has suddenly peaked. In this instance BESS would be strategically deployed for the use case to provide the services required by the T&D network. This could simply be additional voltage or current support or a combination of frequency regulation, voltage support and balancing services. Ideally, this service would prove to be financially beneficial for long term energy support services. Especially, for ISO/RTO (Regional Transmission Organisation) such as National Grid in the UK that provides this service.

In 2015, Italy had an excess of wind generation, and the transmission capacity was not enough to transport all this energy to the north of the country, resulting in wind curtailments. The TSO installed a 38.4MW/250MWh sodium-sulphur BESS to absorb the wind energy and use it during later periods, avoiding the need to invest in new transmission capacity. Additionally, this battery provides services such as primary and secondary reserves, load balancing and voltage control.

Table 10 outlines the technical requirements for the RNZB battery to provide this ancillary service. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and state of charge. Additionally, stating the duration of the battery required which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 10: Summary of technical requirements for use in transmission and distribution upgrade deferral [7] [23]

	Required value
Response time	>1000ms
Cycles	Cycles dependent on the frequency of overload of substation on the network in question. Likely to be low compared to other use cases.
RTE	>70%
SoH EoL	>70%
Duration	1h to 4h
C-Rate	<2C
POC voltage	LV, MV and HV depending on the use case

Traditionally, investment in distribution and transmission assets is used to increase their carrying capacity when peak power flows exceed the load-carrying capacity of the network. However, when such congestion events happen infrequently, or for very limited periods, alternative measures such as the implementation of battery storage systems become a viable option. Due to this specific use case of battery systems, it is likely that the annual cycles completed by the battery will be much lower than other grid services that may be provided by BESS. In a similar fashion, the use of BESSs to serve as capacity reserve to defer investment in peaking plants is a use case that is likely to require fewer annual cycles than other grid services.

Due to the wide range potential BESS use cases for upgrade deferral, the required duration and response time of the battery system is likely to vary significantly on a case-by-case basis. However, this can be considered beneficial, as there is likely to be a specific use case well suited to the performance characteristics of most different battery technologies.

1.3.2.6 Power quality (STATCOM)

Power quality shows how well a power system is behaving. Some of the problems that are associated with power quality in the distribution network include voltage drop in the transmission and distribution lines, voltage swelling/

noise and disturbances in waveforms, current surges/noise and waveform distortion, harmonic pollution, and frequency imbalance.

Ideally, the voltage and current in the power system should be in phase and sinusoidal to achieve maximum output. A slight misalignment between the two will lead to a decrease in power factor, thus, lower power delivery. An example of this is a mismatch between supply and demand, where a sudden increase in demand for power causes a peak. The mismatch in demand is predictable for industrial, commercial, and residential uses, but it is tackling the demand that is key issue with power quality. To meet consumer demands, every effort is made by the grid system to encourage extra work via generators. However, in some scenarios the system is not upgraded enough to be able to provide both active and reactive power demand, thus leading to voltage drop, stress in load, and misalignment between waveforms causing an imbalance. Other distortions such as noise play a part in distorting waveforms and interrupting the flow of power [18].

A potential solution is the implementation of a BESS which is capable of outputting active and reactive power to adjust any off balances. BESSs can act as a STATCOM with the integration of power electronic inverters to deploy sufficient reactive power required for system restoration. The uses of BESS as a STATCOM are described in section 1.3.2.3.

An example of BESS being deployed for power quality services is the Wartsila battery project that is set to join the Taiwan market to provide ancillary services. Wartsila will deploy a 5.2MW/5.2MWh [24] storage system to support Taiwan's relatively small area of major manufacturing centres. Taiwan is known to be a hub manufacturing for major market tech industries and such development requires high power demand and need to maintain a good quality power. BESS has the capacity to provide Taiwan its ancillary services (grid-balancing, frequency regulation, spinning reserve and supplemental reserve) required to achieve grid stability. It is currently aiming to procure 590MW in energy storage capacity in the next four years and has been approved to deploy 30MW of frequency regulation and fast-response balancing load services.

1.3.3 Consumers (BTM)

1.3.3.1 Energy time of use cost management

Time of Use Cost management (ToU) service also known as a mechanism for implicit demand response is a modern way of boosting clean energy use, reducing carbon emissions, and saving customer expenses. ToU encourages consumers to use energy during off-peak period. A household smart meter can monitor energy costs that is useful in providing its users with information on when it would be financially beneficial to consume energy. This is usually when the electricity prices are cheaper, helping to avoid consumers from demanding energy during peak rate prices. Behind–the–meter (BTM) battery storage systems are very useful in ToU as they reduce the electricity costs by charging the batteries during off-peak hours and when the consumer requires it during peak demand, the batteries are discharged to supply electricity, particularly beneficial as tariff are high during this period. Energy companies are also behind this incentive, providing their customers lower prices at off-peak periods thus relieving pressure of the grid network. An advantage of this service is that customers are allowed to adjust their electricity consumption voluntarily either through automation or manual control. The flexibility of this service allows consumers to observe the periods of high and low prices and make a judgement on how they would like to use their electricity. The energy prices presented to the customers are time-varying, based on the power system balance or on market wholesale price such as day-ahead or intraday price signals. ToU tariff services is known to be a provider to 17 European countries, US, and India.

There are two forms of ToU structures: static and dynamic, shown in the Figure 9. In static ToU the usage is determined in blocks of hours where the cost for a specific time block is defined in advance and remains constant. These blocks of hours are usually a measure of peak and off-peak hours, simply reflecting night and day prices. The block hours can also be segmented to allow for slack periods. Seasonal changes also encounter periods that vary in electricity consumption which are factored in ToU static. It is one of the most common forms of ToU service provided in Europe that has been adapted by countries such as Italy where customers in low-voltage areas are mandatorily given static ToU pricing.

The dynamic structure of ToU, provides real time pricing on an hourly or half-an hour basis to the customers with the use of household meters. Prices are determined close to the real time consumption of electricity based on wholesale market. Countries that have utilized this form of ToU include Estonia, Romania, Spain, Sweden, and the UK.

In some cases, there is opportunity to receive a service of variable peak pricing through a hybrid of static and dynamic ToU. Prices for different periods are specified early on and remain constant; but on-peak prices vary under market conditions. Variable peak pricing currently applies in countries such as Denmark, Norway, and Sweden where customers are charged on a monthly average wholesale market price. Another option is critical peak pricing which is also a combination of static and dynamic. Here, the electricity prices increase to a substantially high rate for a short number of days during the year, this is usually the time when the wholesale market prices have risen in the market to a peak level. A use case of this type of ToU is found to be adapted in French Tempo tariff where prices are fixed for 22 days on a high market rate, however, customers are made aware of this increase. Other countries who also use critical peak pricing include Lithuania, Portugal, Romania, and UK at a smaller scale [25].

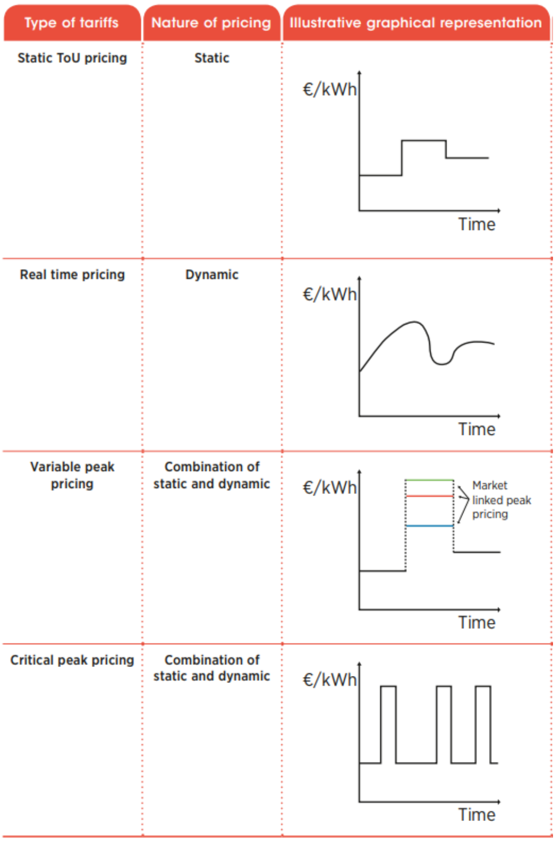

Figure 9: ToU types of tariffs [25]

BTM integration in ToU is not only beneficial for reduced electricity bills for consumers but potentially increasing the use of renewables when coupled with clean generation technologies. A combination of BTM or BESS and generation technologies such as solar PV has been deployed in countries across Europe and useful for residential users who are able to benefit from net billing schemes. This scheme is designed to reflect how much power kWh is consumed by the user and how much is supplied to the Grid. This form of energy consumption incentive was used in the UK, allowing consumer to benefit financially by receiving payment for any excess that could be supplied to the grid.

An example of BESS with ToU is the 3 MW/3.7MWh Li-ion BESS installed in the Arsenal football stadium in 2018 (UK). The aim of this project was to reduce the consumption cost by using a BESS system that would charge up during low peak period and then during high demand, e.g., matches, supply the stadium with energy for a 90-minute period. The combination between BESS and ToU proves a useful incentive for the future, specially, since BESS can operate at synchronicity with ToU structures and demand.

Table 11 outlines the technical requirements for the RNZB battery to provide this ancillary service. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and state of charge. Additionally, stating the duration of the battery required, which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 11: Summary of energy time of use cost management service technical requirements.

	Required value
Response time	1ms – 500s
Cycles[4]	3650 - 5475
RTE	85%
SoH EoL	60% – 80%
Duration	0.5hr – 4 hr
C-Rate	0.25 - 1
POC voltage[5]	MV and LV

A ToU service is designed to allow consumers more control over their electricity demand and to provide a balanced service from the grid system. Ideally in ToU, energy storage will require a fast response in situations where demand for power increases.

For the most part, the peak demand hours are predictable in *static ToU* and last a short period of time. BESS is ideal for this as it can provide power for up to 1hr to 4 hr period with fast response time. However, with a *dynamic ToU* approach, the time scale for a BESS usage will be on an hourly or half-hourly rate. These times will be unpredictable and under such circumstances it is ideal to have a battery technology that is able to withstand quick responses with high energy discharge on shorter time frames.

A high battery cycle is also preferable as ToU service is required to operate at a daily basis and high cycle ensures that a battery can operate for a longer period. Use cases in 1.3.3.1 show that ToU is currently applicable for residential and commercial opportunities therefore mainly operating under medium to low voltage T&D lines.

[4] Defined as $Cycle\ life = \frac{\text{Lifetime throughput}}{\text{Nameplate capacity}}$

[5] This can be classified as High-voltage, Medium-voltage, Low-voltage, or given as an absolute voltage value.

1.3.3.2 Demand side management

Sudden demands in energy consumption can lead to sharp rises in electricity demand in the grid. Unpredictable peak demand is usually met by coal and gas generators to keep a balanced grid system but looking into the future of energy, this is not a viable option. In current energy market, power availability is abundant and more affordable. With the integration of renewables in the last two decades, it is also clean and sustainable.

Demand side management or response (DSM/DSR) is about how to intelligently use this surplus of energy and ensure that the system remains balanced. The DSM service enables consumers, businesses, and other services to have full control in deciding how their electricity is consumed. The choice to control personal demand has a twofold advantage: one is that the consumers can better understand the energy system and how their demands are impacting it during peak hours thus alleviating the sudden peak demand pressure on the grid. The second advantage is a financial incentive added to DSM where consumers can save money on bills.

An example of this is the Irish energy system EirGrid. Ireland has started to adapt to newer technologies and smart grid services of the energy system. For DSM a tariff-based scheme is offered to the consumers of Republic of Ireland (NightSaver) and Norther Ireland (Economy 7) to move their usage to cheaper off-peak times. In addition to this, EirGrid also operates a two-system operator-based scheme knows as Short-Term Active Response (STAR) and Powersave in Ireland that are key to ensuring a balanced and secure grid system operation during stressful periods [26].

In recent years, most DSM techniques have resorted to using BESSs due to their flexibility in supplying energy with fast and high-power response. During off-peak periods, BESS is charged to its full potential and then evenly discharged during a peak period. The wider the off-peak interval, the higher the probability for BESS to cover all possible peak occurrences. However, currently the issue with BESS in DSM lies in narrow peaking periods that BESS is unable to meet. With a short time interval, BESS has a much denser discharge and at occasions will miss the opportunity to provide energy to these demands [27]. Research to tackle this issue is on-going, with the understanding that BESS has potential to provide wider support to DSM, covering more of the techniques.

Table 12 outlines the technical requirements for the RNZB battery to provide this ancillary service. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and state of charge. Additionally, stating the duration of the battery required which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 12: Summary of demand side management service technical requirements.

	Required value
Response time	1ms – 1000ms
Cycles[6]	>365 cycles/year
RTE	>85%
SoH EoL	>80%
Duration	1hr – 4hr
C-Rate	0.25C – 1.0C
POC voltage[7]	MV and LV

[6] Defined as $Cycle\ life = \frac{\text{Lifetime throughput}}{\text{Nameplate capacity}}$

[7] This can be classified as High-voltage, Medium-voltage, Low-voltage, or given as an absolute voltage value.

Demand side management as the name suggests is to control the sudden peak demand of power from the grid. This service allows consumers to have more control over when the demand is made and when it is more economic to do so. Currently, the service is mainly operational in residential areas, mainly operating under medium and low voltages and has the potential to operate for industrial demands. Since demand only covers the sudden peak rises this is likely to be for periods of time e.g., 1hr – 4 hrs where BESS will need to be able to discharge for these durations. The battery cycle itself will be subject to how much BESS support is required, it maybe that BESS will only charge and discharge a few times a day, therefore, a BESS system with a high number of cycles would be ideal. For a battery that will require almost daily usage, the RTE is preferable to be above 85% to ensure good charge and discharge as well as high number of cycles.

1.3.3.3 Back-up power supplies

Back-up power supplies are essential in providing a support system that can be relied on during emergency outages related to grid failures or weather-related incidents. Industrial and commercial trades such as hospitals, emergency services, space and defence, data centres and manufacturing facilities require a constant supply of power to function. Sudden black outs or power cuts can sometimes have severe consequences and global impacts, in some cases life threatening. BESS is ideal in providing a secure supply of electricity via the grid until the off-balance system is back online. This is particularly useful in areas with unreliable power systems or islands that rely on small grid systems with minimal service upgrades. BESS can be installed independently or integrated with an existing back-up generator to operate as an uninterruptible power supply (UPS).

BESS is usually designed with integrated power electronic converters to provide a fast, efficient, and reliable service. It also allows the connection of low voltage energy storage device to the grid in an optimal manner and energy decoupling. In research and development today, converters are being designed to produce better controllability with improvements in ensuring frequency is stabilised for longer periods of time, better quality of voltage support and more control in active and reactive power flow. With rapid advancements in technology, it is likely that in the future, BESS will have the opportunity to operate under a faster response time and have the capacity to support for longer periods of time.

Tesla has recently won to deliver Japan's first battery storage megapack order [28]. Tesla will be delivering a Li-ion based BESS project that provides opportunity to help stabilise the grid system on the northern island of Hokkaido. The Megapack will be 1,523.8kW/6,095.2kWh and initially participate in wholesale energy market and eventually be rolled out to support supply and demand on the island as well as act as a backup power supply unit for residents in the event of power outages or disasters, supporting evacuation centres, allowing mobile phone charging and other necessary requirements.

Although Japan has just started to adapt the deployment of large-scale batteries, this will change in the next few years. Residents are installing home batteries to act as a back-up, but the overall market does not support front of meter ancillary services yet. The requirement to have a reliable back-up service is becoming more and more common globally, BESS is growing as an adaptable residential service with many consumers relying on it and it is likely that this form of service will be widely adapted and used in the future not just residentially but also commercially and industrially.

Table 13 outlines the technical requirements for the RNZB battery to provide this ancillary service. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and state of charge. Additionally, stating the duration of the battery required which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 13: Summary of back-up power supply service technical requirements.

	Required value
Response time	1ms – 300ms
Cycles[8]	>365 cycles/year
RTE	>90%
SoH EoL	>80%
Duration	Dependant on situation. This could be an hour to several hours of support required.
C-Rate	Dependent on duration.
POC voltage[9]	HV, MV and LV

One of the most important services provided by BESS is the back-up power supply. It is essential for emergencies and situations that require immediate attention. The amount of time the back-up services required is dependent on the situation, this may be short term only lasting a few hours or long term required for several hours. Due to the unpredictable nature of this service the battery performance is especially important, and should have high RTE, high response time, state of health and End of Life to ensure it can perform for any duration of time. A low self-discharge is also desirable due to the infrequent nature of this service. Currently, back- up services are required for power cuts and blackouts in residential, commercial, and industrial locations, therefore, highlighting that this service will be connected to high, medium, and low voltage areas.

1.3.3.4 Increased renewables self-consumption (load shifting, load levelling)

Increased self-consumption of energy has allowed a variety of renewable integration into the grid. Solar panels are one of the most popular uses of clean energy sources globally. The energy generated by solar is intermittent not always meeting consumer demand, particularly during the seasonal variation, weather changes and variation in irradiation levels. During high irradiation, solar panels can produce a surplus amount of energy that is either consumed locally or can be sent to the main distribution grid for transmission to other locations. Electricity demand varies considerably depending on the consumer.

Commercial and industrial consumers demand more energy with factories/businesses operating throughout the day whereas residential consumption peaks in the morning and evening (not meeting the actual electricity-generating hours between 12 pm – 4 pm). When consumption exceeds the energy generated, additional energy is drawn from the grid. To create a good balance in the system as well as lower overall electricity cost, load shifting is used. This is a combination of peak shaving and load levelling that allows for energy to be generated during periods of low demand (off-peak) and be stored until needed.

When demand for consumers peaked for a short period, energy was generally supplied by fast-acting peak load generators. Peak shaving is defined as the clipping of peak demand, where the load is now supplied by stored energy (ESS). As a result, there is less pressure to provide immediate energy generation on demand and the grid has an increased load factor, reduction in power charges and increased return of investment. The principle of load levelling allows for the load to be rescheduled to an off-peak period, so energy is generated and stored during this

[8] Defined as $Cycle\ life = \frac{\text{Lifetime throughput}}{\text{Nameplate capacity}}$

[9] This can be classified as High-voltage, Medium-voltage, Low-voltage, or given as an absolute voltage value.

time. Subsequently, this can then be used during the peak demand period to create a greater balance in the grid system. Effectively reducing the cost of electricity during peak periods and enabling stable prices for consumers.

For a more financial incentive, companies with large electricity bills have chosen to side with the Behind-the-meter installation of BESS. Operating largely residentially, this idea is set to revolutionise the decrease in energy costs and improve carbon emissions. Currently, BTM Solar installations struggle to exceed 40% of self-consumption, however, the use of BESS is highly complementary for solar energy. The use of BESS for consumer consumption allows for the battery to be charged by the solar PV directly. Energy stored by BESS would be discharged for local consumption, especially when the PV system is generating insufficient electricity (e.g., during night-time), thus increasing self-consumption. Another benefit for BTM BESS in Solar PV would be the installation would act as an UPS providing electricity during cuts and blackouts.

There are also opportunities for the user to optimise their investment in localised PV and BESS integration, by comparing electricity costs with PV and BESS installation plus usage without purchasing any electricity supply from the grid. If local costs are cheaper, then there is potential for financial incentive with an increase in self-consumption. Additionally, some end users may have the option to sell stored energy to the local grid for further financial incentives.

An example of a large scale solar and storage deployment is in Australia. In 2019, it was announced that a 1.5GW solar and 500MWh battery project by Sunshine Energy located in Queensland will be development, the largest solar project to enter development. Sprawling across 2,055 hectares it will connect a 275kV to Queensland costing approx. $3.5 billion. This project is estimated to produce 2,259GWh of clean energy supplying electricity to 300,000 households [29].

Table 14 outlines the technical requirements for the RNZB battery to provide this ancillary service. The table looks at the batteries response time, number of cycles, round trip efficiency (RTE), state of health and state of charge. Additionally, stating the duration of the battery required which is subject to change depending on the service provided. Finally, the table also looks at the battery C-rate and point of connection to understand if the battery will be providing services to High/Medium/Low voltage connections.

Table 14: Summary of increased renewables self-consumption service technical requirements.

	Required value
Response time	1ms – 200ms
Cycles	>365
RTE	>0.85
SoH EoL	>80
Duration	Only required for peak periods – short duration of 1-4hrs
C-Rate	0.5C – 1C
POC voltage	HV and LV

There are multiple opportunities for BESS in the increased self-consumption of renewables. This system allows the peak demand to be levelized with the help of a BESS. Using techniques such as peak shaving and load levelling, the sudden rises in peak demand can be controlled better by the grid system without the added stress to provide power. These peak demands will vary depending on the consumer itself.

For a residential consumer using renewables power, there will be predictable demand charges, usually during the morning and evening. Therefore, a BESS system with a short duration time is required e.g., 2hr – 4hr. The same does not apply for commercial and industrial for which the demand maybe high during the day, although for short periods of time. The battery designed for this system will need to have a higher cycle for operation as the batteries may be charged and discharged several times a day. Additionally, looking at the use case example in 1.3.3.4 of 500MWh BESS deployment in Australia, the POC of this would be high voltage and low voltage.

1.4 RNZB grid services compliance assessment

This section of the documents aims to assess the suitability of the RNZB technology for use in the energy storage services outlined in Section 1.3 of this document. The current performance data for the RNZB technology (as of the start of the LOLABAT project) has been used for this assessment, alongside the projected performance data (targeted for the end of the LOLABAT project). Table 15 provides a key for use throughout this section of the document.

Table 15: Key for the assessment of RNZB compliance with service technical requirements

Meaning	Assigned colour
RNZB performance values meet the technical requirements of the service	Green
RNZB performance values do not meet the technical requirements of the service	Orange
RNZB performance value range partially meets, or is very close to meeting, the technical requirements of the service	Yellow

1.4.1 RNZB performance consideration

Table 16 and Table 17 show the characteristics of the RNZB as defined as initial point in LOLABAT project and as final point or at the end of LOLABTA project, respectively.

Table 16: The current RNZB performance data (at the beginning of the LOLABAT project)[10]

	Current RNZB value
Response time	1ms – 100ms
Cycles	1000 - 2000
RTE	86% to 89%
SoH EoL	70% to 80%
Duration	0.33h to 10h
C-Rate	0.1C to 3C
POC voltage	Dependent on BoP infrastructure

Table 17: The projected RNZB performance data (at the end of the LOLABAT project)[11]

	Target future RNZB value
Response time	1ms – 100ms
Cycles	2000 - 4000
RTE	86% to 89%
SoH EoL	70% to 80%
Duration	0.33h to 10h
C-Rate	0.1C to 3C
POC voltage	Dependent on BoP infrastructure

[10] Real performance of RNZB 60Ah cells, Sunergy data.
[11] Estimated performance of RNZB cells at the end of LOLABAT project, Sunergy data.

One of the key parameters that will determine the suitability of the RNZB for use in stationary applications is the price (alongside the corresponding performance) of the battery cells. Table 18 below compares the current price and the projected future price of the RNZB battery compared to the key competing battery technology (Li-ion) for stationary battery storage applications.

Table 18: Summary of current and future RNZB prices alongside key competitors [30]

	Current RNZB value	Projected RNZB value	Li-ion (2020)	Li-ion (2023 projected)
Price (€/kW)	55 - 100	40 – 70	NA	NA
Price (€/kWh)	200 - 260	140 - 180	118	87

1.4.2 Compliancy with service requirements

1.4.2.1 Generation services

Dispatchability for renewables

Table 19 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 19: RNZB performance in terms of dispatchability for renewables service requirements

	Current RNZB value	Projected future RNZB value	Required value
Response time	1ms – 100ms	1ms – 100ms	1 – 5 seconds
Cycles	1000 - 2000	2000 - 4000	>365 cycles/year
RTE	86% to 89%	86% to 89%	>90% @ DC level
SoH EoL	70% to 80%	70% to 80%	70%
Duration	0.33h to 10h	0.33h to 10h	1h – 4h
C-Rate	0.1C to 3C	0.1C to 3C	0.25C – 1C
POC voltage	Dependent on balance of plant infrastructure	Dependent on balance of plant infrastructure	MV or HV

Dispatchability for renewables consists of grid firming, ramp rate control and energy time shift services. These services provide support for the grid system to maintain the sudden demand for power, daily. Under the requirements of the service, the RNZB technology is able to meet some of them. The response time for this service being between 1-5 seconds, currently the RNZB target does fulfil this requirement with faster response time than required. Dispatchability service may be required to perform two cycles per day, therefore a high number of cycles are ideal. RNZB target shows that it should perform between 1000-2000 cycles meeting this service requirement, although, the projected future values suggest this will be improved to 2000 – 4000 cycles. The round-trip efficiency value of RNZB falls slightly below the desired >90% range. On a direct current level, the service requires a performance of 90% or above in round trip efficiency, this would ensure that the battery is able to charge and discharge with fewer losses. Currently, the target for RNZB sits very close to the requirements at 86% to 89% and can be suggested suitable for use. The state of health and end of life for RNZB is targeted to be around 70% to 80% and is projected to stay the same in the future, suggesting suitable battery compliance with the service.

Generator hybridisation

Table 20 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 20: RNZB performance compared to generator hybridisation service requirements

	Current RNZB value	Projected future RNZB value	Required value
Response time	1ms – 100ms	1ms – 100ms	Milliseconds to seconds
Cycles	1000 - 2000	2000 - 4000	1 cycle per day
RTE	86% to 89%	86% to 89%	>80%
SoH EoL	70% to 80%	70% to 80%	70%
Duration	0.33h to 10h	0.33h to 10h	0.5h-1h
C-Rate	0.1C to 3C	0.1C to 3C	<1C
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	MV-HV

The current cycle life of 1000-2000 (100% Depth of discharge (DoD) at the start of the LOLABAT project) corresponds to a likely service life of approximately 2.7 – 5.5 years prior to a required cell refresh. This estimate is based on 365 cycles per year. With the targeted cycle life looking to improve to 2000 – 4000 (100% DoD) cycles by the end of the LOLABAT project, the potential service life may be extended to 5.5 – 11.0 years before a cell refresh is required. Considering the typical project lifespan of 20-30 years, one or two cell refreshes is typical for a project for use in this service. If the higher end of the targeted cycling performance of the RNZB battery is achieved, it would be considered suitable for use in this service. It is worth noting that the projected service life will increase if the required cycles are at a reduced depth of discharge.

Whole-sale market arbitrage

Table 21 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 21:: RNZB performance compared to whole-sale market arbitrage service requirements

	Target future RNZB value	Projected future RNZB value	Required value
Response time	1ms – 100ms	1ms – 100ms	1 to 5 seconds
Cycles	1000 - 2000	2000 - 4000	>365 cycles/year
RTE	86% to 89%	86% to 89%	>90%
SoH EoL	70% to 80%	70% to 80%	>80% (desirable)
Duration	0.33h to 10h	0.33h to 10h	1h to 4h
C-Rate	0.1C to 3C	0.1C to 3C	0.25C to 1.0C
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	MV and HV

Currently, the RNZB battery meets most requirements within the wholesale market arbitrage service. The RTE is close to the required value of 90% or above, suggesting that the targeted design is suitable for this service. Although, a higher value of RTE would ensure fewer losses in the battery charge and discharge during operation.
The current cycle life of 1000-2000 (100% DoD the start of the LOLABAT project) corresponds to a likely service life of approximately 2.7 – 5.5 years prior to a required cell refresh. This estimate is based on 365 cycles per year. With the targeted cycle life looking to improve to 2000 – 4000 (100% DoD cycles) cycles by the end of the LOLABAT project, the potential service life may be extended to 5.5 – 11.0 years before a cell refresh is required. Considering the typical project lifespan of 20-30 years, one or two cell refreshes is typical for a project for use in this service. If the higher end of the targeted cycling performance of the RNZB battery is achieved, it would be considered suitable for use in this service. It should be noted that the projected service life estimates increase if the required cycles are at a reduced depth of discharge.

Mini-grids

Table 22 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 22: RNZB performance compared to mini-grid requirements

	Target future RNZB value	Projected future RNZB value	Required value
Response time	1ms – 100ms	1ms – 100ms	100ms to 5s
Cycles	1000 - 2000	2000 - 4000	2000-4000
RTE	86% to 89%	86% to 89%	>80%
SoH EoL	70% to 80%	70% to 80%	60%-70%
Duration	0.33h to 10h	0.33h to 10h	2h-4h
C-Rate	0.1C to 3C	0.1C to 3C	<0.5C
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	LV-MV

If the required cycles for this application are based on 100% DoD, the current cycle performance of the RNZB battery (as of the start of the LOLABAT project) is below the required level for use in a mini-grid application. However, if shallower DoDs are required, the RNZB in its actual state, could address this application. If the projected cycle performance value that is targeted for the end of the LOLABAT project is reached, the RNZB battery will meet the mini-grid performance requirement at any required DoD. All other technical characteristics of the RNZB battery align with the mini-grid requirements.

1.4.2.2 Transport services

Frequency response

Table 23 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 23:RNZB performance compared to frequency response service requirements

	Current RNZB value	Projected future RNZB value	Service requirements
Response time	1ms – 100ms	1ms – 100ms	15 – 30 seconds (primary) 30 – 100 seconds (secondary) 5 – 15 minutes (tertiary)
Cycles	1000 - 2000	2000 - 4000	Continuous >365 cycles/year at 80% depth of discharge (desirable), frequency response Minimum cycles/year, 10 – 50, operating capacity
RTE	86% to 89%	86% to 89%	>90% (desirable)
SoH EoL	70% to 80%	70% to 80%	>80% (desirable)
Duration	0.33h to 10h	0.33h to 10h	15 seconds up to 15 minutes (primary) 30 seconds up to 15 minutes (secondary) 5 minutes up to 2 hours (tertiary)
C-Rate	0.1C to 3C	0.1C to 3C	0.3C – 1.5C
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	MV or HV

The current cycle life 1000-2000 (100% DoD at the start of the LOLABAT project) corresponds to a likely service life of approximately 3.4 – 6.8 years prior to a required cell refresh. This estimate is based on 365 cycles per year at an average 80% DoD. With the targeted cycle life looking to improve to 2000 – 4000 (100% DoD cycles) cycles by the end of the LOLABAT project, the potential service life may be extended to 6.8 – 13.6 years before a cell refresh is required. Considering the typical project lifespan of 20-30 years, one or two cell refreshes is typical for a project for use in this service. If the higher end of the targeted cycling performance of the RNZB battery is achieved, it would be considered suitable for use in this service.

It is worth noting that whilst the RTE of the RNZB battery is slightly below the desired 90% value for Frequency Response, this is unlikely to significantly impact the suitability of the RNZB battery for use in this service.

Operating reserve

Table 24 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 24: RNZB performance compared to operating reserve service requirements

	Current RNZB value	Projected future RNZB value	Service requirements
Response time	1ms – 100ms	1ms – 100ms	1ms to 500ms
Cycles	1000 - 2000	2000 - 4000	1500 - 3000
RTE	86% to 89%	86% to 89%	>75%
SoH EoL	70% to 80%	70% to 80%	70%
Duration	0.33h to 10h	0.33h to 10h	15 minutes to 2+ hours
C-Rate	0.1C to 3C	0.1C to 3C	1C - 4C
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	MV and HV

All the technical requirements for the Operating Reserve service are met by the RNZB battery or have ranges that at least partially overlap with the required values. However, this is unlikely to be a limiting factor due to the infrequent operation of batteries in this range.

Whilst the cycling performance of the battery is currently only partially compliant with the requirements of this service (if the service requires 100% DoD), if the projected future cycling performance of the RNZB battery is met then this will likely exceed the minimum performance requirements.

Voltage support

Table 25 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 25: RNZB performance compared to voltage support service requirements

	Current RNZB value	Projected future RNZB value	Service requirements
Response time	1ms – 100ms	1ms – 100ms	1ms to 2000ms
Cycles	1000 - 2000	2000 - 4000	1000 - 2000
RTE	86% to 89%	86% to 89%	>50%
SoH EoL	70% to 80%	70% to 80%	>80%
Duration	0.33h to 10h	0.33h to 10h	Up to 1 hour
C-Rate	0.1C to 3C	0.1C to 3C	NA
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	MV and HV

The current and future performance characteristics of the RNZB battery easily meet and often exceed the minimum required performance values for use in the Voltage Support service.

Black start

Table 26 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 26: RNZB performance compared to black start requirements

	Current RNZB value	Projected future RNZB value	Service requirements
Response time	1ms – 100ms	1ms – 100ms	1ms to 1000ms (within an instruction timeframe, e.g. 2 hours for the UK National Grid service)
Cycles	1000 - 2000	2000 - 4000	Low number of cycles due to the infrequent nature of this service
RTE	86% to 89%	86% to 89%	>75%
SoH EoL	70% to 80%	70% to 80%	80%
Duration	0.33h to 10h	0.33h to 10h	The ability to provide multiple black starts is likely due to possible tripping during the re-instatement period. E.g. UK National Grid requires the ability to provide at least 3 black starts.
C-Rate	0.1C to 3C	0.1C to 3C	UK National Grid requires the capability to accept instantaneous loading of demand blocks in the range of 35MW to 50MW
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	MV or HV

The response time, cycling ability, RTE, and SoH at EoL performance characteristics of the RNZB battery all comply with the requirements of the Black Start service. Both the duration and C-rate requirements of this service are less simply to define and depend on the exact details of the contract awarded and market in which it is participating. The battery should be sized suitably to be able to handle the demand blocks without exceeding the C-rate limits of the RNZB technology. Typical C-rates are unlikely to be required to be larger than the upper-limit of the RNZB technology. Furthermore, depending on the length of the demand blocks, and the required number of black starts to be provided, the battery capacity (and therefore duration) will need to be specified accordingly. It is unlikely that this service would require a battery duration outside of the RNZB limits specified.

Transmission and distribution upgrade deferral

Table 27 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 27: RNZB performance compared to transmission and distribution upgrade deferral requirements

	Current RNZB value	Projected future RNZB value	Service requirements
Response time	1ms – 100ms	1ms – 100ms	>1000ms
Cycles	1000 - 2000	2000 - 4000	Cycles dependent on the frequency of overload of substation on the network in question. Likely to be low compared to other use cases.
RTE	86% to 89%	86% to 89%	>70%
SoH EoL	70% to 80%	70% to 80%	>70%

Duration	0.33h to 10h	0.33h to 10h	1h to 4h
C-Rate	0.1C to 3C	0.1C to 3C	<2C
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	LV, MV and HV depending on the use case

The RNZB technology is compliant with the transmission and distribution upgrade deferral performance requirements.

Power quality (STATCOM)

See Voltage Support service compliancy provided in section 1.4.2.2.

1.4.2.3 Consumer services

Energy time of use cost management

Table 28 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 28: RNZB performance compared to energy time use cost management requirements

	Target future RNZB value	Projected future RNZB value	Required value
Response time	1ms – 100ms	1ms – 100ms	0.001s – 0.5s
Cycles	1000 - 2000	2000 - 4000	3650 - 5475
RTE	86% to 89%	86% to 89%	85%
SoH EoL	70% to 80%	70% to 80%	60% – 80%
Duration	0.33h to 10h	0.33h to 10h	0.5hr – 4 hr
C-Rate	0.1C to 3C	0.1C to 3C	0.25 - 1
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	MV and LV

If the required cycle life for this application is based on 100% DoD, the current targeted battery cycle for the RNZB is lower than the required amount for ToU operation. This service will be in daily use with possible one to two cycles per day, possibly more if the dynamic approach is taken, therefore, a higher number of cycles will be suitable. Overall, the RNZB can meet most of the service requirements including suitable SoH and EoL, fast response time and good RTE.

Demand side management

Table 29 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 29: RNZB performance compared to demand side management service requirements

	Target future RNZB value	Projected future RNZB value	Required value
Response time	1ms – 100ms	1ms – 100ms	0.001s – 1s
Cycles	1000 - 2000	2000 - 4000	>365 cycles/year
RTE	86% to 89%	86% to 89%	>85%
SoH EoL	70% to 80%	70% to 80%	>80%
Duration	0.33h to 10h	0.33h to 10h	1hr – 4hr
C-Rate	0.1C to 3C	0.1C to 3C	0.25C – 1.0C
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	MV and LV

RNZB targets are compliant with all demand side requirements bar one. The current RNZB targets show to achieve a fast response time within the required time frame. However, a target battery cycle of 1000 to 2000 is considered low under the requirement of demand side management. Overall good RTE value suggesting RNZB will have a good energy discharge and within the scope of desired battery duration as well as end of life margins.

The current cycle life 1000-2000 (100% DoD the start of the LOLABAT project) corresponds to a likely service life of approximately 2.7 – 5.5 years prior to a required cell refresh. This estimate is based on 365 cycles per year. With the targeted cycle life looking to improve to 2000 – 4000 (100% DoD cycles) cycles by the end of the LOLABAT project, the potential service life may be extended to 5.5 – 11.0 years before a cell refresh is required. Considering the typical project lifespan of 20-30 years, one or two cell refreshes is typical for a project for use in this service. If the higher end of the targeted cycling performance of the RNZB battery is achieved, it would be considered suitable for use in this service. It should be noted that the projected service life estimates increase if the cycles are at a reduced depth of discharge.

Back-up power supplies

Table 30 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 30: RNZB performance compared to back-up power supply requirements

	Target future RNZB value	Projected future RNZB value	Required value
Response time	1ms – 100ms	1ms – 100ms	0.001 – 0.3
Cycles	1000 - 2000	2000 - 4000	>365 cycles/year
RTE	86% to 89%	86% to 89%	>90%
SoH EoL	70% to 80%	70% to 80%	>80%
Duration	0.33h to 10h	0.33h to 10h	Dependant on situation. This could be an hour to several hours of support required.
C-Rate	0.1C to 3C	0.1C to 3C	Dependent on duration.
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	HV, MV and LV

In back-up power supplies, it is difficult to suggest the exact duration of battery required as this service answers to situations where the duration may last a little as half an hour or several hours (e.g. 7 hours). Ideally, under this service it would be good to have a battery duration that is able to cover power loss for longer periods of time. Additionally, the number of RNZB cycle shows to be above the required rate, however, this is subject to change depending on the use of service. In some instances, such as continuous power cuts experienced in specific locations, batteries may have to operate for more than two or three cycles a day. The current target RTE for RNZB shows it is suitable for this service. Following this, all other services required for back-up power are met by the RNZB targets.

The current cycle life 1000-2000 (100% DoD the start of the LOLABAT project) corresponds to a likely service life of approximately 2.7 – 5.5 years prior to a required cell refresh. This estimate is based on 365 cycles per year. With the targeted cycle life looking to improve to 2000 – 4000 (100% DoD cycles) cycles by the end of the LOLABAT project, the potential service life may be extended to 5.5 – 11.0 years before a cell refresh is required. Considering the typical project lifespan of 20-30 years, one or two cell refreshes is typical for a project for use in this service. If the higher end of the targeted cycling performance of the RNZB battery is achieved, it would be considered suitable for use in this service. It should be noted that the projected service life estimates increase if the cycles are required at a reduced depth of discharge.

Increased renewables self-consumption

Table 31 provides a comparison between the current performance of the RNZB technology, the projected future performance of the RNZB technology (targeted for the end of the LOLABAT project), and the required performance to provide this service.

Table 31: RNZB performance compared to requirements for increasing renewables self-consumption

	Target future RNZB value	Projected future RNZB value	Required value
Response time	1ms – 100ms	1ms – 100ms	0.001 – 0.2
Cycles	1000 - 2000	2000 - 4000	>365 cycles/year
RTE	86% to 89%	86% to 89%	>0.85
SoH EoL	70% to 80%	70% to 80%	>80
Duration	0.33h to 10h	0.33h to 10h	Only required for peak periods – short duration of 1-4hrs
C-Rate	0.1C to 3C	0.1C to 3C	0.5C – 1C
POC voltage	Dependent on BoP infrastructure	Dependent on BoP infrastructure	HV and LV

Increased self-consumption is a consumer-based response service. The amount of energy consumed and the sudden rise in demand depends greatly on what the consumer has decided, in some situations such as residential applications this is more predictable. Consumers are likely to require power for a short period of time, 1hr – 4hr, in the evening. On the other hand, consumers based commercially and industrially will have a different response and may require power for longer periods. Currently, RNZB can fulfil this requirement as well as all other service requirements within self-consumption. RNZB targets show good margins of RTE, SoH and EoL, response time and battery cycle. Although, the number of cycles may be low considering how often this service is required in the future. It is possible that the batteries may be required to operate more two cycles per day specific to deployment.

The current cycle life 1000-2000 (100% DoD the start of the LOLABAT project) corresponds to a likely service life of approximately 2.7 – 5.5 years prior to a required cell refresh. This estimate is based on 365 cycles per year. With the targeted cycle life looking to improve to 2000 – 4000 (100% DoD cycles) cycles by the end of the LOLABAT project, the potential service life may be extended to 5.5 – 11.0 years before a cell refresh is required. Considering the typical project lifespan of 20-30 years, one or two cell refreshes is typical for a project for use in this service. If the higher end of the targeted cycling performance of the RNZB battery is achieved, it would be considered suitable for use in this service. It should be noted that the projected service life estimates increase if the cycles are required at a reduced depth of discharge.

1.4.3 RNZB grid services compliance improvements

One of the most important performance characteristics for usage in the reviewed energy storage services is the cycle life of the RNZB battery. For multiple cases, the current cycle life performance (at the start of the LOLABAT projects, based on 100% DoD) of 1000 – 2000 cycles is below the required value for a number of energy storage applications. These applications typically require daily cycles from the battery, resulting in a projected service lifetime of 2.7 – 5.5 years based on current RNZB performance data. This assessment assumes that the daily cycles required by these services are at 100% DoD. If the DoD per cycle is reduced, then the projected service lifetime for RNZB will increase accordingly. Assuming a required DoD of 100%, the services which may require performance beyond the current RNZB capabilities include:

- Frequency response

- Whole-sale market arbitrage
- Demand side management
- Energy time of use management
- Operating reserve
- Generator hybridisation
- Increased renewables self-consumption
- Back-up power supplies

However, when considering the projected future cycling performance of the RNZB battery (targeted for the end of the LOLABAT project), the projected value of 2000 – 4000 cycles will increase the viability of using RNZB batteries in all these services. Obtaining cycling performance closer to the higher end of the projected performance range (4000 cycles) will be crucial in ensuring the competitiveness of the RNZB technology for use in these services, pushing the estimated service life to greater than 10 years before a cell refresh is required.

A number of services, such as Frequency Response and use in back-up power supplies require high RTE performance from potential batteries. The RNZB battery's RTE performance is very close to the desired level of >90% in both of these cases, but it is worth considering that battery technologies with better performance in this area may be used in preference due to this limitation. For reference, battery technologies such as Li-ion LFP (Lithium iron phosphate) and NMC (Nickel Manganese Cobalt) can achieve RTE performance in the range of 90-97%.

Systems designed for high power application most commonly reach a DC bus voltage in the range 1000V-1500V DC both due to standard and power electronics limitations. Due to the limited voltage of the RNZB cell compared with other technologies such as Li-ion, to reach the same DC bus voltage, an RNZB will require approximatively three time the number of cells in series. This will induce further complexity in the pack assembly, BMS design and during the operation of the battery and is identified as a risk for this technology. Potential mitigation could be the use of a dual stage power conversion system as detailed in section 1.5.2.

1.4.4 Standards and legislation compliance

Deliverables 2.2 and 2.3 of this work package provide a review of the standardisation and regulatory aspects of BESS projects, respectively. Compliance of the RNZB is dependent on the specific details of the local grid code or the system within which the BESS will be operating. As such to assess fully the legislation and standards compliance requirements would require further work in the identified market.

1.5 RNZB grid integration guidelines

This section contains the grid integration guidelines for the RNZB battery technology. First each level of RNZB integration is described with a bottom-up approach and a clear description of each component is given from the cell to a containerised solution as depicted in Figure 10. Then an installation protocol is given where each step of the installation is described. Finally, specific requirements are given for each application segment.

Figure 10 RNZB integration path

1.5.1 Battery pack assembly configuration

Commercial battery packs for grid applications are usually assembled in modules and enclosed with a BMS, auxiliaries and safety components in a containerized solution. Depending on how modules are connected in the final assembly, the requirements regarding the application or regulatory constraints may vary. This design choice also influences the installation of the RNZB on site.

Several module connection layouts are possible, the most common ones being the singe stage and two stage power conversion as shown in Figure 11. The single stage power conversion is used in most large-scale battery projects to this day. In this configuration, modules are within the range 2-6kWh and assembled in series to reach a voltage between 800V-1500V. Thanks to the limited weight and voltage of each module, installation in racks can be done either at the factory or on site by qualified technician. For the latter, modules are conditioned in pallets and shipping is eased as the number of modules can be adjusted to global and local transport regulation. The two-stage layout uses a DC to DC power converter between the module and the main inverter. Recent largescale battery deployment worldwide shows that in this configuration the modules tend to be larger within the range 70-120kWh. This design allows much more flexibility and is getting traction thanks to continuous improvements of DC to DC power converters. On the other hand, it requires that the modules are assembled in the container at the factory and transported to site fully assembled which can be an issue for weight limits or safety regulation (See D2.3 for transport regulation).

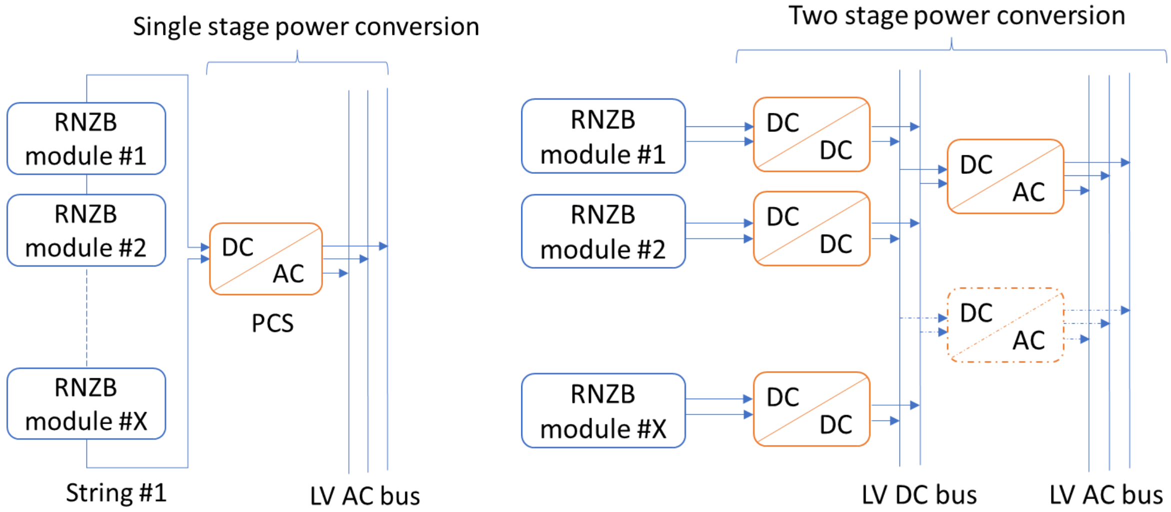

Figure 11: Series/parallel modules assembly

1.5.2 Power conversion system (PCS)

The Power Conversion System (PCS) is a critical part of a battery project as it controls the power flow between the battery and the grid. Depending on the project size and integrator design choices, PCS can either be integrated within the containerised solution or separated in its own enclosure. The benefit of an integrated PCS is its compactness and the reduction of LV DC cabling which reduces the costs and Electromagnetic Compatibility (EMC) emissions. On the other hand, maintenance can be more complex compared to a split battery/PCS configuration. Installation of PCS on site is drastically simplified when integrated as it will be most likely installed and configured to the application requirement at the factory.

The inverter technology can also affect the installation procedure on site. There are two main power converter topologies for battery inverter, the standard two-level inverter and multilevel inverters. The latter has been continuously favoured for its higher power capability and lower current harmonic distortion as per IEC 62933 [31] standard. As such a multilevel inverter requires less footprint which is ideal for a fully integrated solution. The reduced harmonic content allows to lower the switching frequency for increased performance, but the main downside is an increased noise of the PCS. Depending on the local regulation on noise emission, this configuration could require sound suppression measures such as shielding, filtering, or the installation of an acoustic fence. It should be noted that the recent development of silicon carbide (SiC) semiconductors has renewed the interest of the two-level topology. Thanks to the high switching capabilities of this technology manufacturers can now achieve lower harmonic content with a two-level inverter, while also significantly reduce noise emission, thus not requiring noise cancellation measures.

1.5.3 Containerised solution

Grid scale battery manufacturers and integrators have developed modular systems that enables containerised solution. This allows to include all equipment in a standardised container, assemble the components in a controlled environment (i.e. in the factory), ease transportation and installation. Containers can include all components necessary for the operation of the battery or can be split in multiple containers depending on manufacturer design choices or regulatory constraints. The standard approach consists of including the following components, though some of them can be installed externally:

- Battery modules
- BMS
- Power Conversion System
- Temperature management (HVAC)
- LV DC and AC switchgears
- Safety elements (fire detection and suppression system)

The main advantages of a fully containerised solution are a fast installation time, a safer system regarding fire propagation, a more efficient thermal management and easier transportation. In this case, most of the installation work consists in the base foundation and the electrical connection to the transformer (if external).

1.5.4 Transformers

Transformers are necessary pieces of equipment to interface a battery to the grid. The main objective of the transformer is to perform a voltage adaptation for the LV output of the PCS to the grid voltage. It also provides galvanic insulation which is critical for the earthing design. Depending on the grid voltage, several transformers might need to be cascaded to be cost effective and to provide redundancies.

1.5.5 Switchgear

Battery project connected to the grid at the Medium Voltage and upward will require a switchgear. The reliability of the electrical grid is directly dependent on the switchgear, which basically consists of switches, fuses and circuit breakers used to manage electrical equipment. The switchgears are generally installed in a separate building/container with all control and communication systems (SCADA).

Gas insulated switchgear (GIS) is the most common type in largescale battery projects and has sealed enclosures filled with insulating gas sulphur hexafluoride (SF6) or mixture of SF6 and other insulating gases recently released to the market. The gas-filled sealed enclosure facilitates a compact, low-profile installation. The use of gas as an insulating medium, when compared to similar air-insulated switchgear, allows for the distance between interrupting components to be reduced. Gas insulated switchgear should be designed and tested in accordance with IEC 62271 [32] standard.

1.5.6 Installation steps

Depending on the battery system design and application requirements, installation steps can vary significantly. A fully containerised solution is a simpler system installation compared with the installation in a custom-made dedicated battery room. The latter being often offered as a packaged design by an integrator, it is not necessary to describe the steps related to this process and thus, only the containerized solution will be described in this section. The installation steps starts when the battery is about to leave the factory and ends when the system is online and fully tested. The installation steps are the following:

Factory Acceptance Test (FAT)
FAT is a necessary step to ensure that the battery conforms to the customer's quality and performance expectations before transport. Points to be checked are detailed in IEC 61439 [33] (c.f. deliverable D2.2 and D2.3) and are composed of mechanical and electrical tests. At this point the capacity of the battery should be measured along with internal impedance and leakage currents. Tests and quality insurance process might also be witnessed by a third-party technical advisor for larger contracts in order to avoid dispute.

Transport
Transport of the battery is a critical part of the process as various climatic and handling conditions can be encountered. This is the part where most of the damages can occur. Damages can range from container integrity losses to extreme temperature or cell vibration and shocks. A data recorder can be placed in each container to monitor and record these values in the event thresholds are crossed. The State of Charge (SoC) should be set to the optimal value prior to transport to avoid premature calendar ageing, especially if the transport includes long storage periods. In addition, transportation documentation and packaging requirements have to meet the transport codes (i.e. ADR for road, IMDG for maritime transport, RID for rail transport and IATA for air transport; see D2.3. for more information).

Installation on site - Civil work
Prior to the arrival of the battery containers on site, foundation, cabling trenches and earthing system have to be designed and executed according to the manufacturer specifications and application requirements. Health and Safety aspects have to be carefully met to minimise the risk for the project.

Installation on site - Electrical work
Once the battery containers are installed on their respective pads, electrical work can begin. It consists in the connection of power, auxiliaries, and communication cables.

Cold commissioning

At this stage the system is not energised yet. The cold commissioning step enables to check if all mechanical and electrical work have been done according to the specifications. It is also the opportunity to check if the configurations of various systems are effective (BMS, SCADA, HVAC).

Hot commissioning

At this stage most of the testing as proven the battery to be correctly installed and ready to be energised. Energisation will be done iteratively by testing each subsystem step by step. In a containerised solution, each battery rack would be energised one by one until the container is fully operational. Providing the transformer is energised, the PCS is energised following the manufacturer procedure and the power setpoints is adjusted to progressively ramp up/down the output power up to the nominal power.

Site Acceptance Test (SAT)

Once the battery is online, the SAT can be formally executed. The scope of the test can vary depending on the application or the local grid code, but in general it consists of performance tests that guarantee that the battery performs as expected. Tests that can be conducted are the following:

- Response time
- Dischargeable capacity
- Round trip efficiency
- Auxiliary consumption
- Noise emission
- Fault ride through capabilities
- Emergency procedure

When the SAT is formally accepted by the client, the responsibility is often passed from the entity responsible of the construction to the owner or a mandated company like an operations and maintenance (O&M) contractor for example.

1.5.7 Application specific requirements

Depending on the application, design and installation requirements may vary significantly. As such this section addresses variation in the battery integration to give further context for each market segment.

1.5.7.1 Generation

In this section some application specific requirements associated with the use of an RNZB battery in a hydraulic powerplant are described. Most comments are generic as we could not find feedback from a plant operator, but it covers all the issues that could be encountered when installing a battery on a hydro-electric production site. A grid scaled power plant will produce AC power. For this reason, the battery connected on the power side of the production unit, will always come with a power electronics level for the conversion from DC to AC. In this section the battery is considered together with its power electronics interface.

Footprint

Regarding the footprint of the installation of a battery pack, the contracting authority must integrate the constraints related to the connection of the battery on the existing equipment. In the best case, the battery will find a place outside the plant, but in some cases, it might be installed inside the cavern where the available space is limited. In this case, the ability of the battery to be friendly in closed environment will be challenged: flammability, release of toxic gases, resistance to humid environments, etc.

Point of connection
Regarding the point of connection of the installation, the ESS performances such as PQ diagram, voltage level at connection point, harmonic content, etc. will have to support the specifications that come from the applicable grid code and the existing equipment of the plant.

Safety
Regarding the safety concerns, the applicable norms, and standards to battery systems inside powerplants shall be respected.

Reliability
Regarding the reliability concerns, as the ESS will only bring additional functionalities to the plant, but no critical support, the level of functional failure acceptable for the battery system, or the number of acceptable failures per year, shall be defined by finding a technical-economic balance regarding the expectancies of the plant operator.

Applicable grid code
The most critical item regarding the installation of a battery inside a hydro-electric plant may be the applicable grid code items that might prevent such installation of battery within an existing powerplant; if not, the certification process will vary depending on the geographical region.

1.5.7.2 Transport

For both use cases identified in section 1.3.2, and framed within the energy storage application under analysis, the specific requirements to consider, e.g., related to the connection point and reliability requirements specificity, as well as general safety concerns, are similar, given the nature of the use cases that within the scope of the ancillary services primarily target frequency regulation, based on capacity and response. Most European system operators already have worked or are working on applicable grid code guidelines for the connection of energy storage assets that may cover operating capacity and participate in frequency response schemes.

The size of storage systems to be used in frequency response mode is proportional to the grid or balancing area in which they are needed. Generally, storage systems in 20MW and greater size can provide effective frequency response due to their fast action. Some studies [34] have shown that the frequency response from battery storage is twice as effective as a conventional fossil-fuelled generator, including combustion turbines and coal units. However, the location of the storage asset, with respect to other generation, transmission corridors and loads, plays a crucial role in the effectiveness as a frequency response resource.

Operating capacity as a supplemental reserve emerges from the need of fast acting resources. The operation of an electric grid requires reserve capacity that can be called upon when some portion of the normal electric supply resources become unavailable unexpectedly. Generally, reserves are at least as large as the single largest resource (e.g., the single largest generation unit) serving the system and reserve capacity is equivalent to 15% to 20% of the normal electric supply capacity. For synchronised spinning reserve, defined as unloaded generation capacity that is online and ready to serve additional demand, capable of responding within 10 minutes to compensate for generation or transmission outages, or frequency-responsive spinning reserve, that can respond within 10 seconds to maintain system frequency, energy storage based on batteries may also be impactful, since spinning reserve is the first type used when a shortfall occurs.

Unlike generation, since generation resources used as reserve capacity must be online and operational – i.e., at part load –, in almost all circumstances, storage used for reserve capacity does not discharge at all, and it just has to be ready and available to discharge when needed.

Typical storage system sizes range between 10 – 100 MW and target discharge duration ranges of 15 minutes up to 1 hour, performing minimum cycles/year, between 20 – 50 [34].

Applicable grid code items on point of connection and reliability requirements
Regarding the connection code and the applicable technical, design and operational criteria, the following categories must be considered, also linked to the connection site and interface point conditions:

- Grid frequency variations, that in exceptional circumstances could rise to 52 Hz or fall to 47 Hz, and for which is required to withstand and maintain operation for at least 90 minutes (f > 51 Hz or f < 49), 15 minutes (f > 51.5 Hz), 20 seconds (f < 47,5) or sustain a continuous operation (49 ≤ f ≥ 51)
- Grid voltage variations, with normal operating ranges within ±5% and ±10%, depending on the transmission system's nominal voltage
- Impact on voltage waveform quality, namely harmonic content and phase unbalance
- Voltage fluctuations at the point of common coupling, for which $|\%DV_{max}|$ and $|\%DV_{steadystate}|$ should remain under 1% for normal occurrences and under 3% for fault restoration
- Fault ride through capacity and withstand fault clearance times

Regarding the balancing code, particularly the frequency control process, the generic guidelines for assets operating in accordance to become eligible to provide primary and secondary frequency response:

- Frequency sensitive mode when transferring active power to the system
- Required response to high and low frequency

1.5.7.3 Consumers

In this section some application specific requirements associated with the use of a RNZB battery at the consumer level are described. As consumers can range from residential to large Commercial and Industrial (C&I) users, requirements might vary significantly. As such, the focus is put on medium to large C&I users as this is the most demanding application.

Footprint
Regarding the footprint of the installation of a battery for a BTM application, and similarly to the other user segment, footprint is always a concern and while some applications will have available room in a strategic location of a factory floor, some will require a compact system. Most of C&I users prefer deploying current battery technologies like Li-ion outdoor for safety reasons, but if RNZB is proven an order of magnitude safer in regard to thermal runaway and overall general safety, then indoor installation in a compact battery room might be a viable solution.

Point of connection
For BTM applications the point of connection will depend on the C&I consumer nominal contracted power, but an LV coupling would be preferable in order to avoid the need for a transformer. Depending on local consumer grid code, user might also face longer procedure to interface an RNZB at the MV level, thus making the LV option even more attractive.

Reliability
Regarding reliability and depending on the final use of the system (i.e. only as a bill optimisation tool or as a backup power supply) the RNZB might be required to provide excellent reliability with a global availability superior to 98%. This shall be defined by the end user through a technical-economic of potential losses/gain of this technology compared to another.

1.6 Conclusion

An overview of different stationary energy storage services that the RNZB technology may be suitable to be used in has been provided, alongside the technical requirements of the battery to provide these services. Generally, the RNZB technology performance characteristics are in line with the requirements of most of the stationary storage applications and services that have been identified. However, there are some aspects of the RNZB performance that currently fall short of some of the service requirements.

The main limiting factor for the use of the RNZB technology in several of the identified applications and services is the cycle life of the technology. The current cycling performance (around 2000 cycles at 100% DoD at the start of LOLABAT project) is below the minimum requirement of services that require daily cycling (assuming a high depth of discharge required), with service life expected to be below 6 years in this scenario. However, if the upper end of the projected cycling performance is achieved (close to 4000 cycles by the end of LOLABAT project), the RNZB technology will align closely with expected service lifetimes for the applications that require daily cycling. This has been further detailed in Section 1.4.3.

Another limiting factor which may impact the suitability of the RNZB technology for use in Frequency Response and Back-up power supply services is the RTE performance. These cases have a desired RTE performance of >90%, which is slightly higher than the current and projected RNZB performance. This is especially relevant when considering competing battery technologies, such as Li-ion LFP and NMC which can achieve RTE performance in the range of 90-97%.

Systems designed for high power applications most commonly reach a DC bus voltage in the range 1000V-1500V DC. The limited voltage of the RNZB cell compared with other technologies such as Li-ion induce further complexity in the pack assembly, BMS design and during the operation of the battery. This risk could be mitigated with a dual stage power conversion system.

A description of the main components of a grid connected RNZB project has been given. Given the large set of services that the RNZB is compliant with, the focus has been on larger installations that could receive a fully integrated solution in a container but can be scaled down to suit smaller projects. All the necessary steps to integrate an RNZB have been provided in an installation guideline easily digestible.

LOLABAT LONG LASTING BATTERY

References

[1] P. R. e. al, “Electricity Storage and Renewables: Costs and Markets to 2030,” IRENA. International Renewable Energy Agency, Abu Dhabi, October 2017.

[2] RINA Tech UK, *Unpublished internal company document,* 2021.

[3] Steve, “SPE Electrical.,” 23 May 2021. [Online]. Available: https://sp-eng.co.uk/battery-energy-storage-systems-power-arbitrage/.

[4] E. Commission, “Commercialisation of Energy Storage in Europe,” FCH EUROPA, EU, March 2015.

[5] [Online]. Available: https://www.fch.europa.eu/sites/default/files/CommercializationofEnergyStorageFinal_3.pdf.

[6] D. Krishnamurthy, C. Uckun, Z. Zhou, P. R. Thimmapuram and A. Botterud, “Energy Storage Arbitrage Under Day-Ahead and Real-Time Price Uncertainty,” IEEE Xplore , 04 April 2017.

[7] E. Union, “Sustainable Energy Handbook, Module 5.3: Off-grid Rural Electrification - Mini-grid Systems,” 2016.

[8] IRENA, “Utility-scale batteries,” 2019. [Online]. Available: https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2019/Sep/IRENA_Utility-scale-batteries_2019.pdf.

[9] HITACHI, “Reliable, affordable power with substantial energy savings at an industrial facility. Microgrid case study,” HITACHI ABB POWER GRIDS, SA, 2021.

[10] N. S. et.al, “Journal of Energy and Power Engineering,” *Renewable Energy Based Grid Connected Battery Projects around the World - An Overview,* pp. 1 - 23, 2019.

[11] E. C, “Market integration of local energy systems. Is local energy management compatible with European regulation for retail competition?,” Energy, 114 pp. 913 - 922. , 2016.

[12] GMBH, “FLEDHIEM,” 08 2017. [Online]. Available: https://tn.boell.org/sites/default/files/uploads/2017/08/presentation_feldheim_energy_autonomous_village.pdf.

[13] European Network of Transmission System Operators for Electricity, “OPERATIONAL RESERVE AD HOC TEAM REPORT,” 23 May 2012. [Online]. Available: https://eepublicdownloads.entsoe.eu/clean-documents/pre2015/resources/LCFR/2012-06-14_SOC-AhT-OR_Report_final_V9-3.pdf.

[14] E. Union, “METIS Technical Note T4. Overview of European Electricity Markets,” European Comission, February 2016.

[15] NGESO, “Enhanced Frequency Response FAQs v5.0,” 26 March 2016. [Online]. Available: https://www.nationalgrid.com/sites/default/files/documents/Enhanced%20Frequency%20Response%20FAQs%20v5.0_.pdf.

[16] “IEA Energy Storage Tracking report — June 2020”.

[17] National Grid ESO, “Fast reserve,” 15 September 2021. [Online]. Available: https://www.nationalgrideso.com/industry-information/balancing-services/reserve-services/fast-reserve.

[18] National Grid ESO, “Short term operating reserve (STOR),” 13 September 2021. [Online]. Available: https://www.nationalgrideso.com/industry-information/balancing-services/reserve-services/short-term-operating-reserve.

[19] mpoweruk, “Electropedia,” [Online]. Available: https://www.mpoweruk.com/grid_storage.htm.

[20] A. C. e. al., “Integrating STATCOM and Battery Energy Storage System for Power System Transient Stability: A Review and Application,” 17 December 2012. [Online]. Available: https://www.hindawi.com/journals/ape/2012/676010/.

[21] P. Release, “News and Technology for the Global Energy Industry,” *Siemens Energy wins its first black-start battery storage project for power generation in the U.S.,* p. 1, 28 Jan 2021.

[22] National Grid ESO, “Black Start,” October 2012. [Online]. Available: https://www.nationalgrid.com/sites/default/files/documents/Black%20Start%20Service%20Description.pdf.

[23] Ralph Masiello, “Market Design for Congestion Relief with Energy Storage,” QUANTA technology LLC, 2016.

[24] R. Masiello, “Market Design for Congestion Relief,” [Online]. Available: https://quanta-technology.com/wp-content/uploads/2020/05/Emerging-Technologies-White-Paper-Energy-Storage_final3.pdf.

[25] A. Colthrope, “Energy Storage News,” *Wärtsilä battery project to join ‘Taiwan’s competitive market’ for ancillary services,* August 12 2021.

[26] S. M. (. I. Arina Anisie and Francisco Boshell with additional contributions and support by Harsh Kanani, “Time-of-Use Tariffs. Innovation Landscape Brief,” IRENA, 2019.

[27] “EIRGRID GROUP,” 2021. [Online]. Available: https://www.eirgridgroup.com/customer-and-industry/becoming-a-customer/demand-side-management/.

[28] M. A. A. e. al, “Real-Time Demand Side Management Algorithm Using Stochastic Optimization,” energies, 7 May 2018.

[29] A. Colthorpe, “Energy Storage News,” 19 August 2021. [Online]. Available: https://www.energy-storage.news/tesla-wins-first-megapack-battery-storage-order-in-japan/.

[30] M. Maisch, “PV Magazine,” 22 February 2019. [Online]. Available: https://www.pv-magazine.com/2019/02/22/1-5-gw-solar-500-mwh-battery-project-breaks-ground-in-australia/.

[31] BloombergNEF, “Battery Pack Prices Cited Below $100/kWh for the First Time in 2020, While Market Average Sits at $137/kWh,” 20 September 2021. [Online]. Available: https://about.bnef.com/blog/battery-pack-prices-cited-below-100-kwh-for-the-first-time-in-2020-while-market-average-sits-at-137-kwh/.

[32] “IEC 62933: Electrical energy storage (EES) systems,” 2018 .

[33] “IEC 62271-1 High-voltage switchgear and controlgear,” 2007-10.

[34] “IEC 61439: Low-voltage switchgear and controlgear assemblies,” 2020 .

[35] California Energy Storage Alliance (CESA), “ Energy Storage – a Cheaper, Faster and Cleaner Alternative to Conventional Frequency Regulation,” Berkeley, CA, 2013.

[36] M. Pirolli, “Sustainable Energy Handbook,” 8 January 2021.

[37] A. S. et.al, “RENEWABLE MINI-GRIDS - Innovation Landscape Brief,” IRENA, Abu Dhabi, 2019.