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Sodium-Ion and sodium Metal BAtteries for efficient and sustainable next-generation energy storage

GRANT AGREEMENT No. 963542

SIMBA – Deliverable Report

<< D1.1 – Stationary Energy Storage – Use Cases and Requirements >>

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Publishable summary

The objectives of T1.1 of WP1 was formulated as “Testing protocol development - stationary Energy Storage – Use Cases, Requirements and KPI’s” and D1.1 Deliverable is “Stationary Energy Storage – Use Cases and Requirements”. To reach the task goals the work involved the investigation of various stationary energy storage applications as well as the requirements to those systems.

Stationary energy storage is essential factors to incorporate the increasingly large share of solar and wind power in the EU energy mix. Solar panels and wind turbines are energy sources with a higher level of sustainability, they produce practically no carbon dioxide and less depend on natural gas and natural resource harvesting.

In general, the battery system intended for an energy storage application needs to demonstrate general baseline performance characteristics, which include the following:

- discharge performance under various conditions;
- maximum discharge current;
- internal DC resistance;
- endurance under cycling and standby modes.

Depending upon the battery technology evaluation may include the following parameters:

- available energy under constant power (CP) discharge;
- maximum output power under constant power discharge;
- energy efficiency under cycling.

Among the possible applications 6 use cases were considered, namely: batteries for renewable, photovoltaic and wind applications, including small-scale household batteries; telecom power systems; dc power solutions for generation, transmission & distribution; ups/data centers; emergency lighting; generator/engine starting. The first three were finally selected as the most promising from the point of view of the SIB using, and detailed analysis of possible stationary energy storage applications suitable for SIBs was performed.

A set of key performance indicators (KPI) was proposed for each use cases. KPIs have been identified for these applications, and as a guideline, the most critical SIB characteristics to pay attention to could become the low cost of energy/power due to abundance of raw materials, safety of operation, high C-rate (up to 1C or 2C), long life (up to 10 years or up to 3000… 3500 charge-discharge cycles).

Contents

Purpose of the document

This report provides a set of use cases to be suitable and possible for stationary energy storage applications of SIBs as well as Key Performance Indicators (KPIs) for these applications.

1.1 Document structure

N/A.

1.2 Deviations from original description in the Grant Agreement Annex 1 Part A

N/A.

1.2.1 Descriptions of work related to deliverable in GA Annex 1 – Part A

N/A.

1.2.2 Time deviations from original planning in GA Annex 1 – Part A

N/A.

1.2.3 Content deviations from original plan in GA Annex 1 – Part A

N/A.

Introduction

The EU is in transition to a sustainable energy system as laid out in the European Commission's Energy Union strategy [1]. The burning of fossil fuel for electricity and heat is one of the largest sources of global greenhouse gas emissions, which generates ca. 25% of global carbon dioxide emissions. Switching to clean energy is a way to reduce greenhouse gas emissions. To incorporate the increasingly large share of solar and wind power in the EU energy mix, stationary energy storage will be essential. Solar panels and wind turbines are energy sources with a higher level of sustainability, they produce practically no carbon dioxide and less depend on natural gas and natural resource harvesting. Unfortunately, renewable energy sources provide only intermittent power and need proper weather conditions to generate heat or/and electricity. So, they need intermediate elements for continuous system work and such elements for a successful energy transition can be energy storage systems (ESS). A variety of energy storage technologies are currently available, from the pumped hydro storage, heat storage and flywheel to battery storage. Detailed analysis of ESS is given in [2,3,4].

One of the ways to minimize the intermittency issue is battery energy storage systems (BSS). Their share in total ESS is comparable with pumped hydro storage systems [3]. The most promising BSS technologies are lithium-ion, lead-acid, redox-flow, high temperature batteries such as sodium-sulfur, and some other batteries. Lead-acid electrochemical system was historically first to be used in BSS coupled with photovoltaic panels or with wind-turbines. Due to the significant development in the battery technologies over the last decades, the demand for replacing conventional lead acid system with other modern technologies, especially with lithium-ion batteries (LIBs), is rapidly increasing. LIBs using currently dominates in many different industry areas, but growing of their production may soon shift the supply-and-demand balance for lithium into deficit. It may result from reaching limits of both in terms of energy density and cost reduction, and controversial debates on lithium supply cannot be ignored [5,6]. Additional disadvantage of LIBs is that the system may catch fire and even explode due to overvoltage or due to thermal runaway. All above-mentioned drawbacks lead people to look for an inexpensive and safe replacement of Li-ion electrochemical system.

Sodium-ion battery (SIB) technology is the most obvious alternative to LIBs. SIB has two main benefits: cost and safety, with the potential to approach the performance characteristics of LIB, with the lower cost associated with lead acid battery technologies [5]. There is one more advantage of SIB technology –its high similarity to LIB technology, it may be said that the SIB technology is a “drop-in” technology for LIBs [5]. This fact makes easier to organize SIB manufacturing.

The stationary energy storage market is still in its infancy but is expected to grow. As can be seen from [2] the year 2018 was the first in which the revenue of the BSS market overtook the one of the established markets for pumped hydro storage, showing strong growth and relevance in Germany. According to [2] the BSS market can be subdivided into two sub-markets: (1) small PV home storage systems (HSS); and (2) large industrial and large-scale storage systems (ISS). These BSS applications can be also split in groups depending on voltage level, rated power, storage capacity, etc. [2-4].

Analysis of possible stationary energy storage applications was the basis for solving the task 1.1 of WP1. This task was formulated as follows “T1.1 Testing protocol development - stationary Energy Storage – Use Cases, Requirements and KPI’s” and was divided to 2 subtasks:

ST1.1.1: KPI’s for energy storage systems

This work involves the investigation of different stationary energy storage installations, and their requirements. The key requirements for stationary energy storage such as energy density (volumetric and gravimetric), power, cycle life, life-time and cost will be set.

ST1.1.2 Definition of energy storage use cases and testing protocol development

The following use cases will be studied: residential energy storage, with back-up power and peak shaving grid-services. Other grid-related services (e.g. Frequency regulation) will be investigated, and specifically the combination with supercapacitor (from YUN) will be explored. In this subtask typical use case profiles will be translated into testing protocols, which will be implemented throughout the project to assess the batteries on use case specific KPI’s. In residential stationary storage systems, if the presence of solar panels and electric vehicles is included, a battery will be going through multiple charge/discharge cycles per day. Such scenario translates into the C-rate ranging from 0.2 C to 1C (charging/discharging for 5 hours or 1 hour). The efficiency of a battery at different C-rates is an important aspect to come to and for optimization for any specific application.

In general, the battery system intended for an energy storage application needs to demonstrate general baseline performance parameters, which include the following:

- discharge performance under various conditions;
- maximum discharge current;
- internal DC resistance;
- endurance under cycling and standby modes

Depending upon the battery technology evaluation may include the following parameters:

- available discharge energy under constant power (CP) discharge;
- maximum output power under CP discharge;
- energy efficiency under cycling.

Among the possible applications 6 use cases were considered, namely: batteries for renewable, photovoltaic and wind applications, including small-scale household batteries; telecom power systems; dc power solutions for generation, transmission & distribution; ups/data centers; emergency lighting; generator/engine starting. The first three were selected as the most promising from the point of view of the SIB using. Detailed analysis of possible stationary energy storage applications suitable for SIBs are considered in the next chapter of the report.

Stationary Energy Storage – Use Cases and Requirements (technical section)

In this chapter the description of three use cases is provided, which, in our opinion, are the most promising from the point of view of using SIB. Key performance indicators (KPI) will be considered for each case.

1.3 Telecom Power Systems

The scheme of a typical telecom power system is shown in Fig. 1. Base transceiver station (BTS) is the active telecom load. Switched mode power supply (SMPS) and power interface unit (PIU) are the power conditioning units, batteries are the energy storage units. RF and microwave signal produced by the BTS are transmitted and received using antennas mounted on the telecom towers. SMPS produces the required DC power supply required for the operation of BTS by converting the available AC power supply from diesel generator/electric grid to DC. PIU has auto mains failure (AMF) which turns on the diesel generator (DG) when the network grid (NG) supply is not available. All the equipment in the shelter including the BTS are designed to operate at 27 ^{0}C, so it is important to maintain the temperature within the shelter below 30^{0} C. This process of maintaining the temperature of a telecom tower shelter is done by air conditioners [7,8]. Telecom bad-grid and off-grid tower sites may also be equipped with photovoltaic (PV) panels [9].

Batteries provide the 48V DC power to the equipment if the rectifiers fail to do so. In general, batteries are able to ensure the operation of the complex for up to 8 hours. In many instances, telecommunication failures occurred because the batteries were completely discharged before the AC was restored. In other cases, outages occurred because the batteries could not maintain the minimum constant voltage level required to operate the equipment.

Batteries also perform another additional function. As mentioned before, when a loss of commercial AC occurs, it takes 3-4 seconds for the AC transfer switch to transfer the power source from the commercial AC to the generator. During these 3-4 seconds the batteries have to supply the power to the complex. It is important to state here that the battery system helps to maintain an exact streamed -48VDC supplied to the BTS for maximum performance. It is worth noting that the type of a battery used in these systems is referred to as deep cycle batteries. Deep cycle name came from the fact that these batteries can be discharged to zero level and can still be recharged from that zero level back to 100% without any negative effect on the battery cells. Factors that can affect the battery life include: expansion and corrosion of the positive grid structure due to oxidation of the grid and plate materials, design life (normally between 3 to 10 years), loss of active material from the positive plate, elevated temperatures, discharge cycles, DC ripple current, overcharging, undercharging, manufacturing variations, improper storage, over-discharge and misapplications [12].

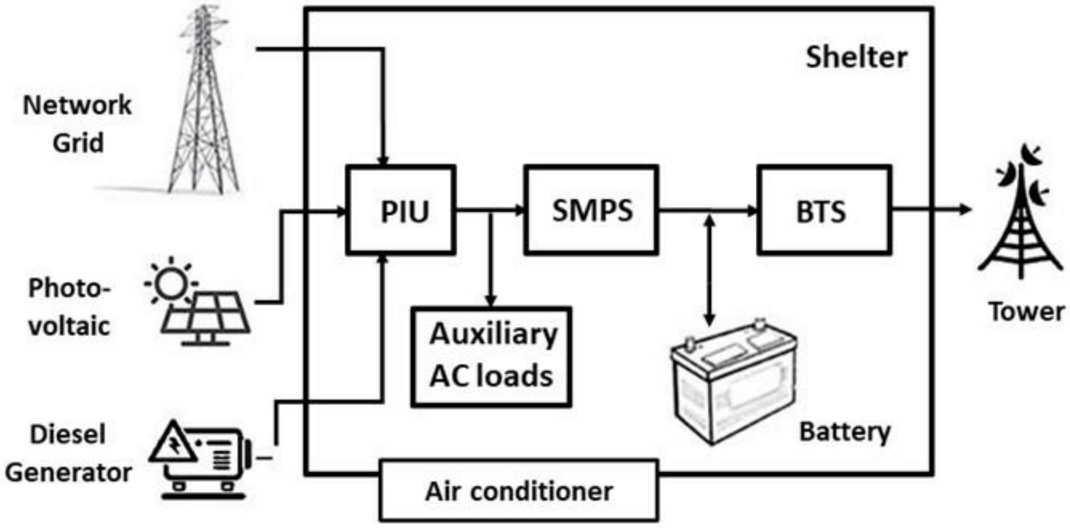

Fig.1. Typical scheme of telecommunication site [10]. In remote off-grid places, PV panels can be also added to the Telecom Power system [9, 11].

As an example, the parameters of telecommunication station are listed in Table 1. They are quotes from [13].

Installation type	Off-grid site
BTS load	~2 kW
DG	30 kW
SMPS voltage	48 V
Battery (LIB) capacity	700 Ah
Battery life	5 years

Table 1. The parameters of telecommunication station with LIB [13].

Based on the foregoing and taking into account the characteristics listed in Table 1, it is possible to formulate additional KPIs for batteries used for telecom application – see in Table 2.

Battery KPIs for telecom application.	Values
Charge rate	0.15-0.2C
Discharge rate	0.1C-0.3C (3-10 hours of tower's work)
Service time	3-10 years
charge/discharge cycles	1000-3500 cycles
Operation temperature	-20 – 50C
Round trip efficiency	90% (@25C, current= 0.2C, 80% DOD)
Self-discharge	<=2% (@25C, month, @3.8V)
DOD	100%

Table 2. KPIs for batteries used in telecom application.

1.4 Batteries for renewable, photovoltaic and wind applications, including small-scale household batteries

Home photovoltaic (PV) is a clean, emissions-free, and renewable energy source. It can significantly reduce the carbon component of humanity's ecological footprint. Solar panels are usually placed on roofs, since they can receive the maximum amount of sunlight there. In Southern Germany power (peak value) of rooftop-systems varies from 3 to 12 kWp (which corresponds to 20 - 80 m^2) with the mean value equal to 5.7 kWp [14]. Price PV rooftop system was ~ 1300 €/kWp at the end of 2019 [15]. Most rooftop PV stations in developed countries are grid-connected photovoltaic power systems, as it shown in Fig. 2. Stand-alone systems, which operate “off-grid”, are not connected to an electricity distribution system and can additionally incorporate wind turbine (WT) and diesel generator (DG). Batteries for “off-grid” households are typically sized to supply the electric load for one to three days (30-90kWh). This “off-grid” case is schematically shown in Fig. 3. For instance, a 1.5-kilowatt wind turbine may provide energy to cover the needs of a home requiring 300 kWh per month in a location with a 6.26 m/s annual average wind speed. Though, there are some well-known wind turbine disadvantages: wind fluctuation, threat to birds, noise pollution and wind turbine safety in a storm.

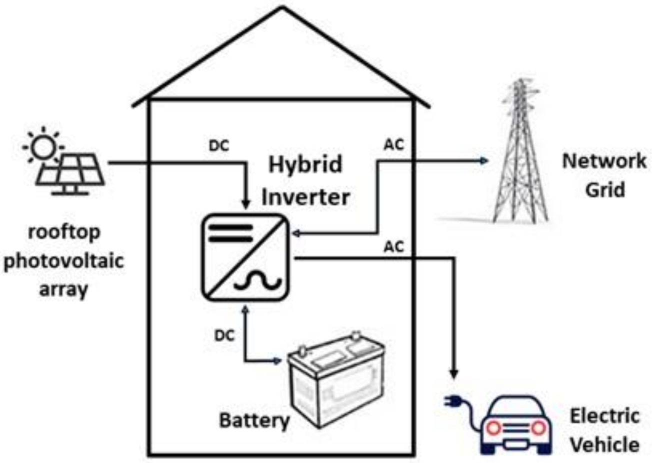

Fig.2. Network grid (NG)-connected Household, equipped with photo-voltaic (PV) panels and battery energy storage system (BSS). Plug-in electric vehicle may also be in use.

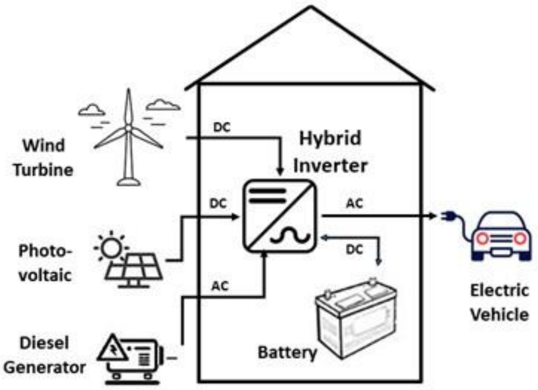

Fig.3. Off-grid Household, which is equipped with photo-voltaic (PV) panels, a wind turbine (WT), a diesel generator (DG) and backup battery system (BSS). Plug-in electric vehicle may also be in use.

Both solar and wind energy depend on changes in weather and are intermittent by nature. Batteries installed in households could alleviate this intermittent issue, by shaving peaks and filling valleys in the household energy demand profiles (Fig.4).

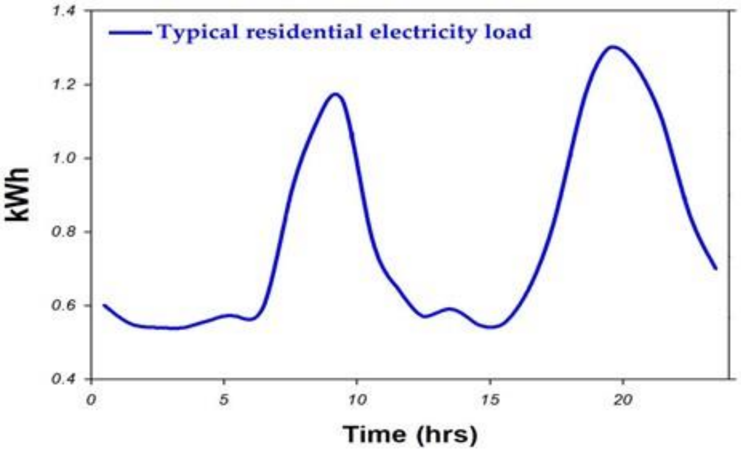

Fig.4. Typical residential house daily electricity load profile [16].

Some economic estimations have been made to find optimal battery capacity to match PV installation [14]. As found, the optimal ratio is roughly 1kWh of battery for each kWp of solar system, e.g. for 6 kWp PV array 6 kWh battery looks the best fit from economic point of view, or taking into account 80% DoD (depth of discharge) total battery energy should be ca. 7.5 kWh. Commercially available batteries have energies up to 14 kWh (Tesla Powerwall 2.00) that may be slightly excessive in average case. For instance, according to the Korean energy census report [17], the average electricity consumption of a residential house is approximately 13 kWh/day. The average consumption significantly varies from country to country. In the USA an average household uses 32 kWh of energy per day (Fig. 5). However, the daily profile of energy consumption stays roughly the same - see in Fig.4.

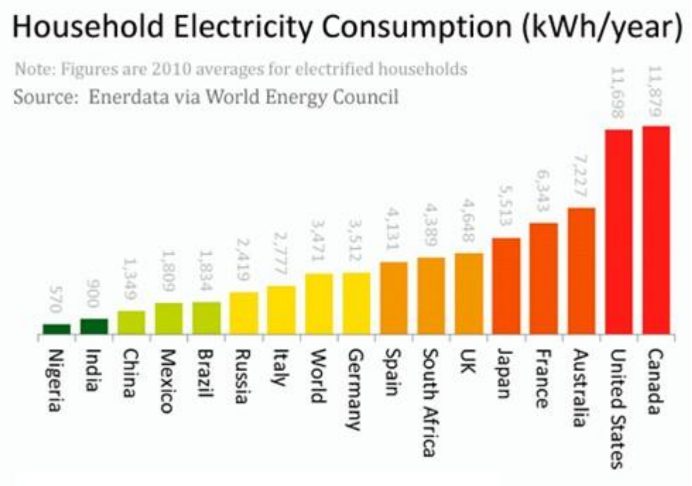

Fig.5. Household electricity consumptions by countries.

Roughly, there are three periods in the daily consumption of electricity:
1) Night time consumption (11 pm – 6am; 7 hours in total) is a time of small electrical load. The so-called "green tariff" is usually referred to this period. During this period, electricity is quite cheap and is usually used to charge an electric vehicle, or possibly to charge a battery system.
2) Morning workload (from 6:00 to 10:00) and evening workload (from 18:00 to 22:00) are periods of increased consumption, usually 2-3 times higher than in period 1. During these hours, the "Red tariff" (more expensive electricity) is used. It's time to drain your battery to minimize costs. The discharge current can reach 1C.
3) The period of maximum generation of photovoltaic modules is normally from 10 am to 4 pm. Sometimes the "Sunshine tariff" is applied in the period [18]. Electricity is cheap and the excess is used to power the batteries to reduce the electricity load. During the period, the electrical load is also quite low (about the same level as in period 1). At this time, the battery charging current may be below C/6.
It is believed that Storage Battery Systems should be 15 years in service, which gives ca. 5000 charge/discharge cycles. As the use of electric vehicles (EVs) grows, this new type of electricity load also impacts on peak electricity demand, especially because a large proportion of motorists seek to recharge their vehicle batteries during the evening. The evening is typically a period of high demand as people return from work, switching on home appliances, lighting and heating/cooling while much office and industrial equipment are still running. There were several attempts to calculate profile of energy consumption with private electric vehicle charging from household outlet, e.g. [19] gives a typical simulated load profile in 3.7 kW home grid. PEV average consumption is 0.186 kWh/km [20] at average trip distance less than 100 km (which gives additional 19 kWh/day in use).
As can be seen from Fig.6, evening load even higher while PEV is used at household. As a result, discharge current of backup battery system should be also raised (from 0.3C up to discharge rate of ca. 1C) in this case.

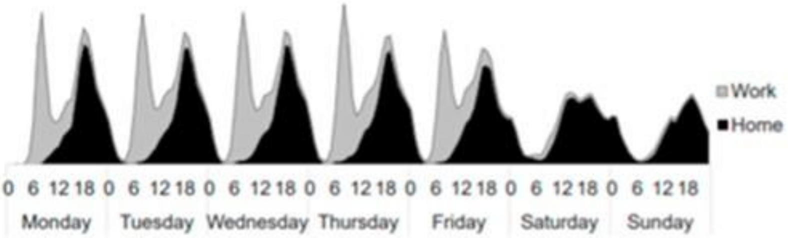

Fig.6. Simulated load profile of PEVs gives charging possibilities at home and at work. Charge with 3.7 kW [19].

KPIs for batteries used for Renewable, Photovoltaic and Wind Applications, including small-scale household batteries are listed in Table 3.

Battery KPIs for peak shaving application.	Values
Discharge rate	1C
Charge rate	0.15-0.2C
Discharge rate (no PEV)	0.3C-0.5C
Discharge rate (PEV is in use)	0.5C-1C
Service time	10 years
charge/discharge cycles	3500 cycles
Operation temperature	-20 – 50C
Round trip efficiency	90% (@25C, current= 0.2C, 80% DOD)
Self-discharge	<=2% per month (@25C)

Table 3. Battery KPI for Renewable, Photovoltaic and Wind Applications, including small-scale household batteries and taking into account a typical daily load profile.

1.5 DC Power Solutions for Generation, Transmission & Distribution (Frequency regulation)

An electric power system can be characterized by the following important parameters: voltage, waveform of a power supply system, and its frequency. The parameters should conform to established specifications. In Europe and in most of Asia countries the most commonly used nominal frequency (NF) in power systems is 50 Hz. In North America NF is 60 Hz.

When the power system operates in a range of frequency (NF ±0.1) Hz, it is considered as standard conditions. If the frequency deviates from NF on ± 1.5 Hz (the value can change from country to country), it is called emergency condition or restoration condition.

Frequency variations in a power system are due to the imbalance between generation and load. When the frequency value of a power system reaches the emergency condition, the frequency control (FC) strategy is initiated. The frequency control is used to maintain the electric frequency at the nominal level by providing upward and downward regulation at different time scales. Upward regulation is provided during negative frequency deviations to increase the frequency, whereas downward regulation is provided during positive frequency deviations to reduce the frequency. The frequency control can be divided into separate control principles depending on the time scale: primary, secondary and tertiary control as illustrated in Fig. 7 [21].

The primary frequency control is activated within seconds of a frequency deviation and is used to stop the change in frequency. The secondary control is then activated within minutes and lasts until the frequency is back to the nominal value. If the secondary control is not enough to bring the frequency back to the nominal value the tertiary control can also be activated.

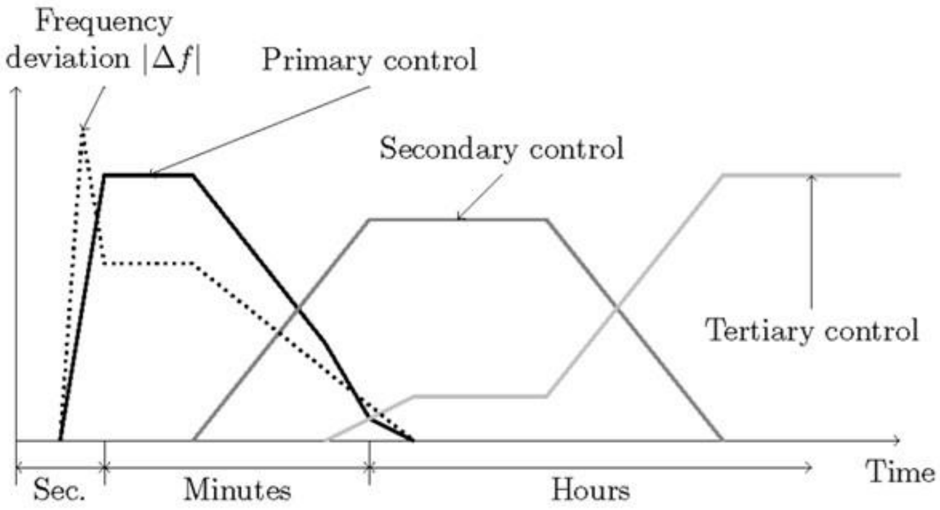

Fig.7. Activation of frequency control principles during a frequency deviation (Δf) in the grid [21].

Primary frequency control: All the generation plants connected in the high voltage power system shall be able to generate the required additional power to balance frequency and keep it from 30 s to 15 min (depending on the requirements of the transmission system operator (TSO)). This primary regulation is mandatory for all the generators (except the renewable energy sources). The replacement of conventional fossil-fuel generators (mostly inertial) by intermittent renewable energy source, such as solar PV and wind turbines, leads to the degradation of the frequency stability [22]. Because of the wide use of renewable energy sources, the frequency regulation in modern power system has become one of the most crucial challenges since the inertia of the grid with renewable energy source is reduced and both generation and demand are stochastic [23]. The quick responsive energy storage technologies, e.g., battery energy storage or supercapacitor storage technology, are recognized as viable to provide frequency regulation in power systems with high penetration of renewable energy sources.

Secondary frequency control. If the frequency value after primary frequency control stage is still deviates from the nominal one, additional generation capacity needs to be started (while the frequency value is lower than the nominal one), while if the frequency value is higher than the nominal one, some generation capacity must be stopped, or the load has to be increased. The secondary control is usually performed automatically by all the generators participating in this regulation (reserve generators).

Tertiary Control. At this stage the TSO asks producers (even those not involved in the secondary control) to start-up generators not operating at that moment. This control level is not automatic but is executed upon request from the grid operator.

Most requirements to a frequency regulation system are described by Protocol for Uniformly Measuring and Expressing the Performance of Energy Storage Systems by the United States Department of Energy (DOE Protocol) [24].

Battery energy storage systems (BSS) are used in the primary and secondary frequency control. Usually, they can produce total power more than 1MW and evenly distributed through the grid. The BSS normally keeps its own charge around 50% SoC. If frequency deviates toward lower values, the BSS discharges itself, delivering electricity to the grid. In case when frequency deviates to higher values, the BSS charges itself, therefore absorbing energy excess from the grid. Also, a BSS must be able to provide symmetric regulation for at least 15 minutes which is known as the 15-min-criterion. This gives us maximum charge/discharge current equal to 2C (in practice, charge/discharge rate is close to 1.3C). Fig.8 illustrates power response characteristics of primary frequency control. As can be seen the power used for primary frequency control (PFC) is activated for negative frequency deviations (Δf) and vice versa. A frequency dead-band (Δf_{db}) can also be allowed where the primary frequency control does not need to be activated.

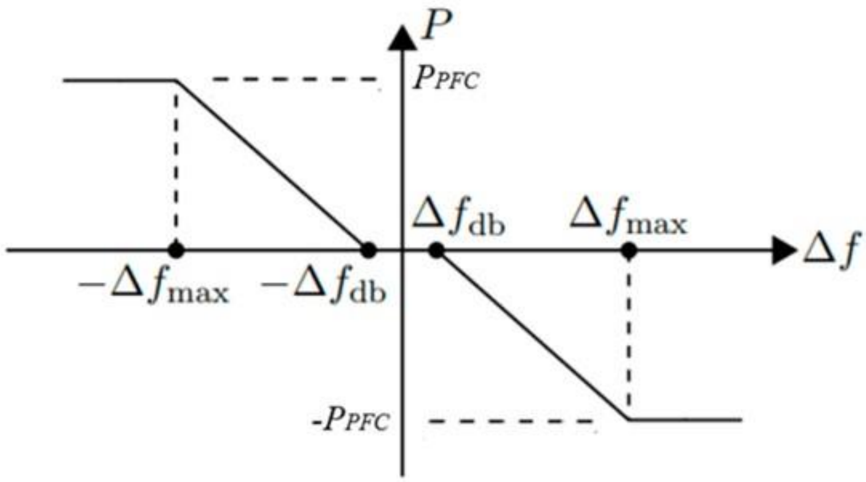

Fig.8. Power response characteristics of primary frequency control [25].

KPIs for batteries used for frequency regulation application are listed in Table 4.

Battery KPIs for frequency regulation application.	Values
Charge rate	1.3C-2C
Discharge rate	1.3C-2C
Minimum bid size	1 MW
BSS SOC	50%
Time response (capability to provide 100% of rated power PFCR within 30 seconds at frequency deviation of ±200 mHz	≤ 30 c
Min energy of BESS (to maintain stable frequency over the time needed for SFC activation: not exceeding 15min)	0.5MWh
Service time	10 years
Cycle life	3000 cycles
Operation temperature	-20… 50 deg.C
BESS round trip efficiency	90% (@25 deg.C, current= 0.5C, 20% DOD)
Self-discharge	≤ 2% per month (@25 deg.C)

Table 4. KPIs for batteries used for frequency regulation application.

Conclusions and Recommendations

Na-ion batteries (SIB) look like a very promising solution capable of replacing Li-ion ones, in particular, in various stationary applications due to the cost, availability and safety consideration.

In this report three most relevant for SIB application areas have been considered, namely,

(1) telecom power systems;

(2) batteries for renewable, photovoltaic and wind applications, including small-scale household batteries;

(3) DC power solutions for generation, transmission & distribution, in particular, for frequency regulation.

KPIs have been identified for these applications, and as a guideline, the most critical SIB characteristics to pay attention to could become the high power output and high C-rate (up to 1C or 2C) as well as long life (up to 10 years or up to 3000… 3500 charge-discharge cycles).

Risk Register

N/A.

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Appendix A - Table of Abbreviations

Symbol / Shortname	
AC	Alternating Current
AMF	Auto Mains Failure
BSS	Battery Energy Storage System
BMS	Battery management system
BTS	Base transceiver station
DC	Direct Current
DoD	Depth of Discharge
DG	Diesel Generator
EES	Electrical Energy Storage
FR	Frequency regulation
GHG	Greenhouse gas
KPI	Key Performance Indicator
LIB	Lithium-ion Battery
SIB	Sodium-ion Battery
NG	Network Grid
PEV	Plug-in Electric Vehicle
PIU	Power Interface Unit
PS	Peak Shaving
PV	Photovoltaics
SMPS	Switched Mode Power Supply
SoC	State of Charge
SoH	State of Health
WT	Wind Turbine

Appendix B- Acknowledgement

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Project partners:

#	Partner	Partner Full Name
1	TUDa	TECHNISCHE UNIVERSITAT DARMSTADT
2	UU	UPPSALA UNIVERSITET
3	UBham	THE UNIVERSITY OF BIRMINGHAM
4	WMG	THE UNIVERSITY OF WARWICK
5	KIT	KARLSRUHER INSTITUT FUER TECHNOLOGIE
6	CEA	COMMISSARIAT A L ENERGIE ATOMIQUE ET AUX ENERGIES ALTERNATIVES
7	IFE	INSTITUTT FOR ENERGITEKNIKK
8	SAS	USTAV ANORGANICKEJ CHEMIE SLOVENSKA AKADEMIA VIED (Institute of Inorganic Chemistry, Slovak Academy of Sciences)
9	FHG	FRAUNHOFER GESELLSCHAFT ZUR FOERDERUNG DER ANGEWANDTEN FORSCHUNG E.V.
10	JM	JOHNSON MATTHEY PLC
11	Elkem	ELKEM AS
12	YUN	YUNASKO-UKRAINE LLC
13	SAFT	SAFT
14	Altris	ALTRIS AB
15	Recupyl	TES RECUPYL SAS
	UNR	UNIRESEARCH BV

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