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Renewable Energy Based Grid Connected Battery Projects around the World—An Overview

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Abstract: The environmental pollution, as well as gradual depletion of mineral resources has encouraged the world to move into renewable energy sources for generation of electricity. At present, the cost of using renewable energy sources, such as sunshine and wind in electricity generation has significantly reduced. This has led to higher penetration of renewable energy into the grid. However, both wind and solar energy photovoltaics are unpredictable energies which reduce the reliability and resiliency of the grid. The integration of battery energy storage system in the grid is one of the proficient solutions to the problem. There are numerous grid connected renewable energy based battery projects that have been deployed in different countries around the world for research, development and commercial application. This review paper will discuss some of the projects based on the battery connected wind and solar energy power generation systems that can operate both in grid connected and grid independent modes. The projects discussed in this paper are selected based on the availability of information. The battery energy storage system (BESS) incorporated in each of the project is found to increase the stability and performance of the grid by addressing the mismatch between power generation and the load of the grid created due to intermittent nature of renewable energy sources.

Key words: Battery technology, grid connected battery projects, power electronics, solar, wind.

1. Introduction

In recent years, the reliable power supply has become a major requirement for any power system. It is more demanding that the energy production (supply) and the load (demand) match always. The deployment of grid connected battery projects around the world has made the difficult task of balancing supply and demand of electricity much easier. A battery technology with a reasonable cost that can perform ancillary services will enable the U.S. as well as other nations to easily integrate the renewable power into their power systems on a large scale. Energy storage system (ESS) has found its application in various fields such as electricity grid, off the grid, rooftop solar panels, hybrid electric vehicles and trains. With the growing population and increasing demand, it is observed that the world will need increased energy supply in the future. The world's primary energy consumption was increased by 1% in 2014, 0.9% in 2015 and 1% in 2016. From Fig. 1a, it is observed that the Asia Pacific contributed 60% of growth. Energy consumption in China has grown by 1.3% in 2016 China is the world's largest renewable power producer. For a 16th consecutive year, China has remained on the top of the world's growth of energy market. In 2016, 14.1% renewable power (excluding hydro) grew. More than half of the renewable power growth is due to wind energy growth. Solar contributes about 18% of the total. The total power generation from renewable energy is 7.5%, which was 6.7% in 2015. Europe & Eurasia shares 11.8% of power from renewable energy sources which is the highest share in the world. However, the smallest increment of share rose in 2016 as shown in Fig. 1b [1].

Corresponding author: Nimat Shamim, Ph.D., research fields: grid integration, battery energy storage, fuel cell, power systems.

2. Energy Sector around the World

Energy production through renewable energy sources (RES) is growing rapidly around the world.

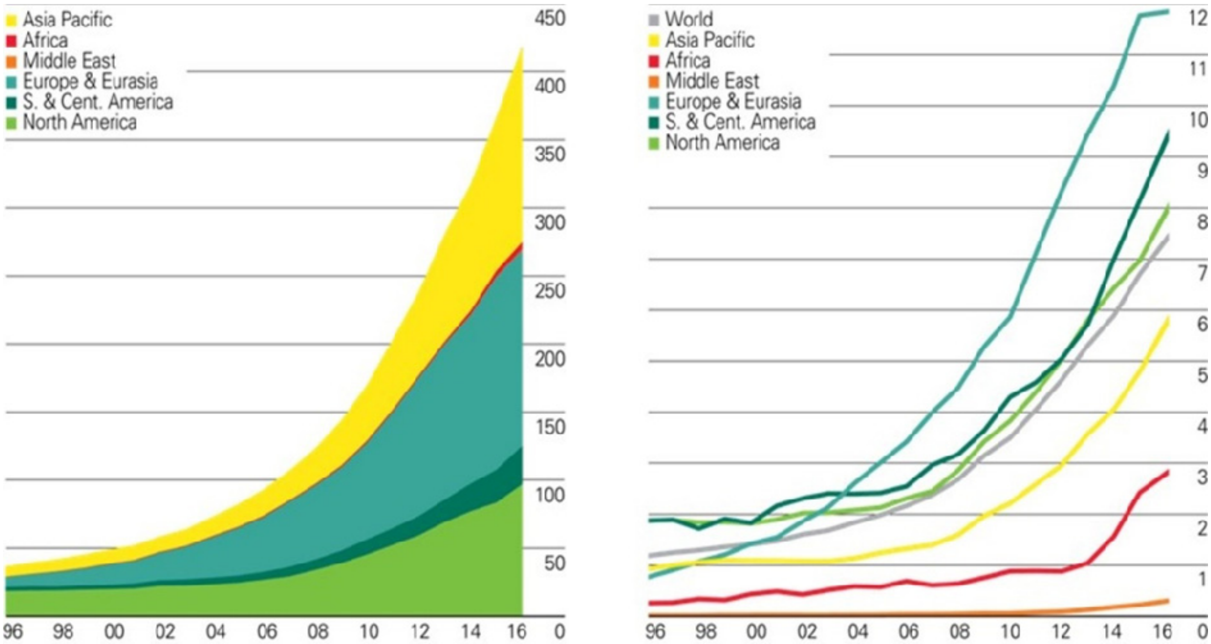


Fig. 1 (a) Renewables consumption by region million tons oil equivalent; (b) Renewables share of power generation by region percentage, BP Statistical Review of World Energy 2017© BP p.l.c. 2017 [1].

Strong cost reduction over the recent years has made it possible for developing countries to deploy RES in their power mix along with developed countries. The Energy Information Administration (EIA) integrates data statistics on renewable energy, productions and energy consumption by different sectors. The available resource is helpful for understanding the energy markets. Fig. 2 shows the world's net electricity generation and prediction for future years by different sources in trillion kilowatt-hours for a time span of 40 years. Over the decades the ratio of primary fuel used to generate electricity had changed. Coal is most widely used in electricity generation. However, its average growth rate is only 0.8%/year. Whereas, power generation by natural gas increases 2.7%/year and energy generation by nuclear increases 2.4%/year approximately [2].

The total generation from renewables (including both hydropower and non-hydropower resources) increases on an average of 2.9%/year. The renewables' share of world power generation will grow from 22% in 2012 to 29% in 2040 according to EIA's prediction. Fig. 3 shows the net electricity generation from different sources of renewables. Electricity generation from wind and PV systems is increasing by an average of 5.7%/year. According to EIA, additional 5.9 trillion kWh of new renewable generation will be introduced to the world total generation over the prediction period [2].

Global wind energy council collects and analyzes wind data in more than 80 countries around the world. Fig. 4 shows the cumulative capacity of wind generated energy in top countries around the world as

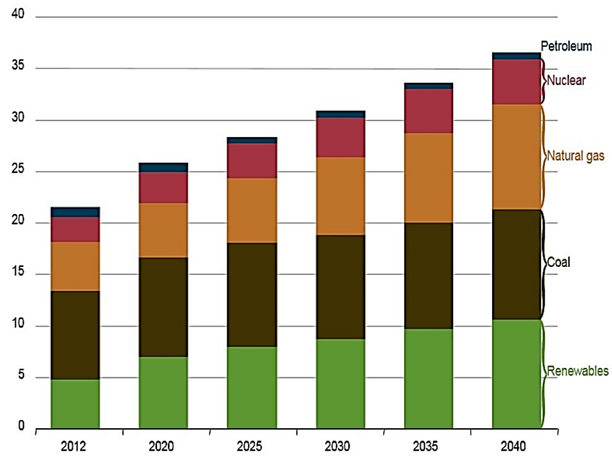


Fig. 2 World's total electricity generation (in trillion kilowatt-hours) by fuel 2012 to 2040 [2].

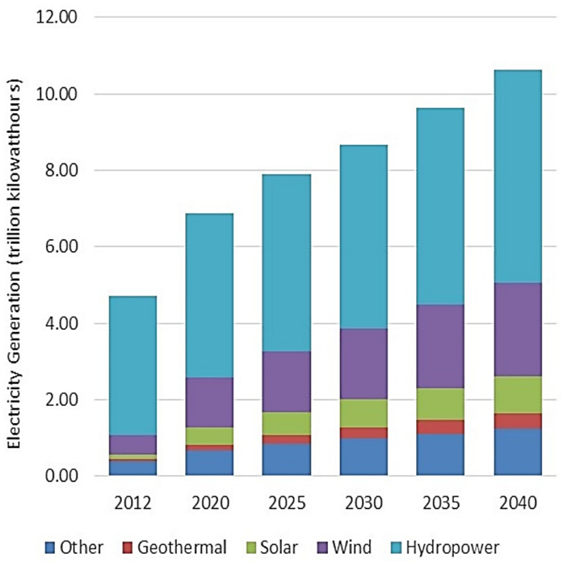
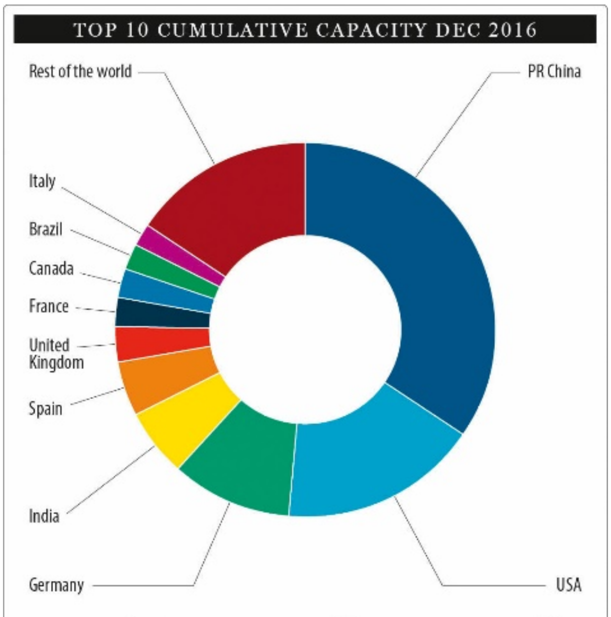


Fig. 3 World net electricity generation from renewable power by fuel, 2012-40 (trillion kilowatt-hours) [2].



Country	MW	% Share
PR China	168,732	34.7
USA	82,184	16.9
Germany	50,018	10.3
India	28,700	5.9
Spain	23,074	4.7
United Kingdom	14,543	3.0
France	12,066	2.5
Canada	11,900	2.4
Brazil*	10,740	2.2
Italy	9,257	1.9
Rest of the world	75,576	15.5
Total TOP 10	**411,214**	**84**
World Total	**486,790**	**100**

Fig. 4 Cumulative wind capacity of top ten countries as of Dec 2016 [3].

of December 2016. China adding 23.4 GW in 2016 is leading the wind market with almost 169 GW installed capacity. USA has a total wind installation of over 82 GW. Wind turbines operating in 40 states generated a record total of 226 million MWh during 2016. Canada with an average growth of 18%/year between 2012 and 2016 has just under 12 GW installed capacity at the end of 2016. European Union has a total of 153.7 GW of installed wind power capacity. Germany is leading with 50 GW. Wind energy represents 17 percent of Europe's total installed power generation capacity. Other countries in the world are also introducing themselves in the wind power market. With 55 GW installations in 2016, the total cumulative installation is about 500 GW in the world [3].

At the end of 2016 global solar PV power generating capacity is about 303 GW [4] around the world with new installations totaling more than 75 GW in 2016. This is almost 33.2% increase on that of the end of 2015. Fig. 5 shows the Solar PV Global Capacity in different countries from the year 2006 to 2016. The largest increment in 2016 was recorded in China (34.5 GW) with a cumulative installed capacity of 78.1 GW. USA has 40.3 GW cumulative installed capacity of Solar Power with 14.7 GW added in 2016. Among the other countries, Japan has 42.8 GW and Germany has 41.3 GW of cummulative solar power [5].

The above analysis on energy scenarios focusing on wind and solar energy trend in world market provides the basis for an understanding on the current energy generation capacity and future projectiles.

3. Overview of Grid Connected Battery Projects around the World

3.1 Lithium-ion Battery Technology

Research Development

The current Li-ion battery technology uses lithium metal oxide, such as $LiCoO_2$ and $LiMO_2$ as the cathode, and graphitic carbon is used as the anode. As

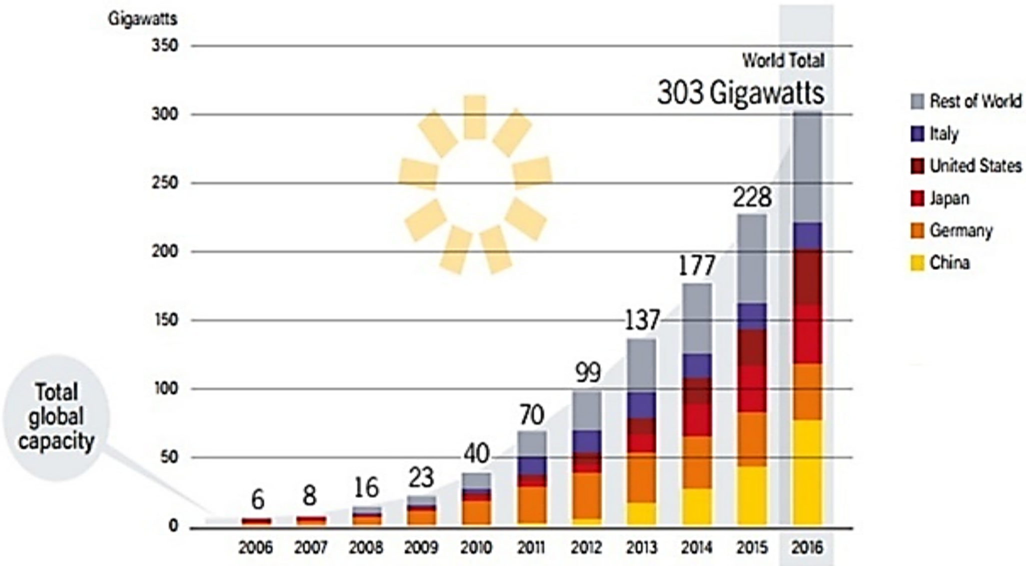


Fig. 5 Solar PV global capacity, by country and region, 2006-2016 [5].

the electrolyte, organic liquid such as $LiPF_6$ salt dissolved in a mixture of ethylene carbonate (EC), dimethyl carbonate (DMC), diethyl carbonate (DEC), ethyl methyl carbonate (EMC) etc. organic solvents is used [6, 7]. The Li-ion battery is widely used commercially for grid connected storage system. Li-ion batteries have a fast response time (millisecond time) and up to 97% high cycle efficiency [8-11]. However, Li-ion battery's lifetime is affected by the depth of discharge (DoD). The overall cost is little higher since the battery pack requires on-board computer for operation management [6].

Current research is mainly focused on increasing the cell voltage and increasing the charge storage capacity. To increase the cell voltage, researchers are focusing mainly on increasing the cathode voltage as the anode (graphite) voltage is already close to that of Li/Li^+ [12, 13]. The increase of cathode voltage is not stable in contact with the organic solvents used in the electrolytes. New electrolytes are being tested so that it is compatible with both anode and cathode at high voltages. The current Li-ion battery technology is based on insertion reaction, to increase the charge storage capacities of both anode and cathode a conversion reaction with lithium is being considered by the researchers [12].

Several companies provide commercially available Li-ion battery technologies for utility scale energy market. Below are some of the projects that use Li-ion batteries.

3.1.1 Zhangbei National Wind and Solar Energy Storage and Transmission Demonstration Project

Project Deployment. One of the largest energy storage projects around the world is deployed in Zhangbei County, Hebei Province in China. The overall investment of the project is 1.89 billion USD. The Zhangbei National Wind and Solar Energy Storage and Transmission Demonstration Project has a plan to have 500 MW of installed wind capacity, 100 MW of installed solar PV capacity and 110 MWh of energy storage. Fig. 6 shows the project site. The total land coverage is 200 square kilometers. The project is deployed by the federally owned State Grid Corporation China (SGCC) utility company. The Zhangbei National Demonstration project is the first "key project" among various demonstration projects proposed by The Ministry of Finance, Ministry of Science and Technology, National Energy Bureau and the State Grid Corporation of China (SGCC). The project started in 2011. The main objective of the project is to use the battery energy system effectively to support, manage and be able to establish an interactive electric power grid [14].

Fig. 6 Zhangbei National Wind and Solar Energy Storage and Transmission Demonstration Project [14].

Battery Technology. In this project 4 lithium-ion battery systems and 1 vanadium redox flow battery system have been used. Lithium-Iron Phosphate battery technology has a service life of over 20 years with peak shaving and load leveling capabilities [15]. The project has 6 MW / 36 MWh Lithium Iron Phosphate battery manufactured by Build Your Dreams (BYD) Auto, 4 MW / 16 MWh Lithium-ion batteries manufactured by Amperex Technology Limited (ATL), 3 MW / 9 MWh Lithium-ion batteries manufactured by China Aviation Lithium Battery Co., Ltd and 1 MW / 2 MWh Lithium-ion battery manufactured by Wanxiang Group and 2 MW / 8 MWh Vanadium Redox Flow Battery system manufactured by Prudent Energy. The total capacity of the energy storage system is 16 MW / 71 MWh. The voltage grade is about 380 V / 50 Hz using Ethernet (Modbus) communication [16].

Wind Turbine and Solar Technology. The Xiaodongliang wind farm (48 MW) and Mengjialiang wind farm (49.5 MW) are a part of this project. The Xiaodongliang wind farm consists of 24 sets of 2 MW doubly fed wind generators [17]. In the first phase 100 MW of Wind, 40 MW of Solar and 36 MWh of battery has been integrated together. The first phase of investment is worth over $500M USD [18].

Control Technology. The XJ Group Corporation in China supplied electrical equipment including photovoltaic inverters, storage systems, transformers, etc. for the project. BYD, Soaring, XJ Group, ABB and Sifang supplied the power electronics for 6 MW, 4 MW, 3 MW, 2 MW and 1 MW battery storage system respectively. The 10 units of PCS100 ESS equipment is provided by ABB. ABB's PCS100 is used to monitor real-time voltage of the power grid and to control the real and reactive power. It helps to integrate battery with other renewable energy sources by adjusting frequency and voltage. It also improves the operational quality, reliability and overall performance of the grid [19].

Applications. Zhangbei National Energy Storage and Transmission Demonstration Project is the world's biggest utility-scale hybrid renewable energy plant. In this project, large scale lithium-ion battery energy storage is integrated with utility-scale wind and solar generation. In future, North China's energy grid will be integrated with the whole system. The energy storage technology plays a significant role in improving the reliability and overall performance such as frequency regulation, ramping, renewables' capacity firming and time shift of the power grid [19]. The primary applications of energy storage are to efficiently integrate wind, solar and other renewable energy sources and to provide frequency regulation and voltage support.

3.1.2 Coweness First Nation

Wind and Storage Demonstration in a First Nations Community, Cowessess First Nation

Project Deployment. The Cowessess First Nation (CFN) project consists of 800 kW wind turbine and 1,000-kWh lithium-ion battery storage system. The project is located on a land 2-km southeast of Regina, Saskatchewan, Canada [20]. The total project cost is $5.5 million. The project received funding from different sources such as the Federal Government's

Clean Energy Fund ($2.78 million), the Saskatchewan government's Go Green Fund ($1.39 million), Indian and Northern Affairs ($248,000), and the Saskatchewan Research Council (SRC) ($180,000). The lead proponent of the project Cowessess First Nation also invested $1.8 million. Fig. 7 shows the project site with the Enercon wind turbine and the battery compound. The main objectives of the project are (1) to demonstrate the consistency and robustness of a wind-storage electric system at Cowesses First nations; (2) to enable the on and off grid scenario of the developed system replicate at other sites of First Nation; (3) to reduce greenhouse gas emission; and (4) to reduce the cost of electric production [20]. The project came online in 2012 [21].

Battery Technology. In this project a lithium-ion battery technology of 740 kWh of electrical storage capacity has been used. The battery system has been developed by the Saft technology with two Itensium Max 20E battery systems. Fig. 8 shows the battery system. The battery system has a total capacity of 1 MWh and has the scalability to allow energy content to be increased in 124 kWh increment. Each of the ESS includes 400 kW power conditioning system [22]. The Saft's li-ion battery technology has the capability to operate in the temperature range of -50 °C to +60° C

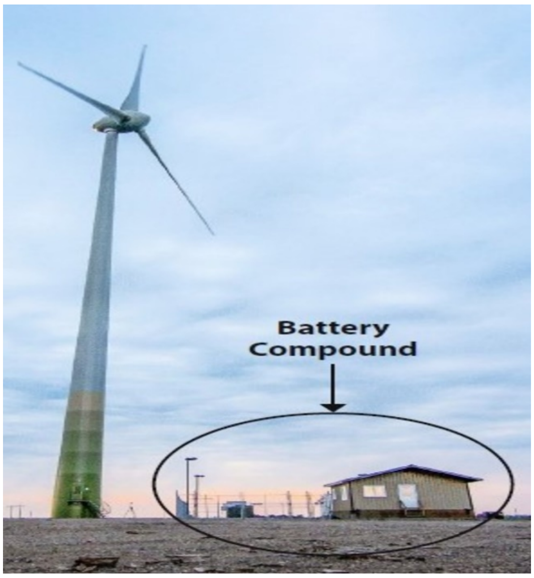


Fig. 7 Project site at Cowessess, Saskatchewan [20].

Fig. 8 Lithium ion battery system [20].

for a standard cell and with an operating voltage range of 4.2 V-2.5 V. They are maintenance-free, reliable and operate at low life cycle cost [23].

Wind Turbine Technology. The Enercon technologies have manufactured the wind turbine (model E53/800) with a power rating of 800 kW for this project. It has three blades with a rotor diameter of 52.9 m and a swept area of 2,198 m^2. The power density is 2.75 m^2/kW. The turbine uses pitch for power controlling. The maximum and minimum rotor speed is 11 radians/min and 29.5 radians/min. The generator of the turbine manufactured by Enercon is synchronous wounded with no gearbox at the turbine. The maximum generator output speed is 28.3 radians/min and the output voltage range is from 400-690 V [24].

Control Technology. The project uses the ABB's EssProPower Conversion System (PCS) to integrate 744 kWh lithium-ion energy storage system with a wind turbine into the electrical grid. Fig. 9 shows the ESS control package. The PCS automatically charges and discharges the battery to maintain the overall system. The controller uses human machine interface communication. PCS can control real and reactive power dynamically, has high and low voltage ride through capability and grid stabilization features such as active damping. It has a fast response to power quality reference signal [25].

Fig. 9 ESSPro PCS control packages /ABB's ESS Pro PCS indoor and outdoor package [25].

Applications. The turbine-battery system produces 2,185 MWh of net electrical energy from the year 2014 to 2015. Revenue collected by CFN is $215,800 at a rate based on power purchase agreement of about $100/MWh. The greenhouse gas emission was also reduced by 969 tons of CO_2 equivalent. The wind turbine can fulfill the annual energy requirement of 300 homes. Lithium-ion battery has a fast response that it can respond to changes of wind within less than one second which makes it capable of smoothing the variable output of wind by 65 to 78% [26].

3.1.3 Bosch Braderup Energy Storage (ES) Facility

Project Deployment. The energy storage project is situated on the North Sea coast, Schleswig-Holstein, Germany. The deployed stationary energy storage facility became operational in 2014 [27]. The community wind farm has 200 private investors and six 3.3 MW wind turbines. The storage facility, situated on former farmland, has a total output of 2,325 kW and a total capacity of 3,000 kWh. The generation is found to be sufficient to meet the electricity needs of 40 average single-family homes for seven days and nights. The vanadium redox flow battery was installed in a building measuring 150 m^2 while the lithium-ion batteries are housed in large steel containers covering an area of around 350 m^2 as shown in Fig. 20. The total area of the installation, including building services and parking spaces, is approximately 2,500 m^2. The double battery at Braderup is one of the largest hybrid energy storage projects in Europe [28].

Battery Technology. The Bosch Braderup energy storage facility uses hybrid energy storage system. The ESS facility has a total capacity of 3 MWh (a 2 MWh lithium-ion storage unit and a 1 MWh vanadium redox flow battery). The hybrid system is designed and built by Bosch. Fig. 10 shows the energy storage facility. The storage plant functions with electronic controls and software specially developed by Bosch. Lithium-ion modules are provided by Sony and vanadium redox flow battery is provided by Vanadis Power GmbH. The storage system is connected to an 18 MW installed capacity wind farm at the local community. The energy storage system is used to save surplus electricity in situations of more power generation than the load by wind. The generated power of the wind is distributed to the suitable battery depending on the charge status of each battery [27].

Wind Turbine Technology. The wind turbines have been installed in two phases. Phase I commissioned in 2005 and Phase 2 commissioned in 2006. Each phase has four Siemens SWT-2.3-101 turbines. Power rating for each turbine is 2,300 kW. The total nominal power

Fig. 10 Bosch Braderup ES facility: li-ion battery [27].

for each phase is 9,200 kW. The wind farm technology has been developed, operated and owned by Bürgerwindpark Braderup [29].

Control Technology. The control electronics design, system integration, and testing of different operating variants in Braderup are performed by Bosh. The storage facility's power electronics can feed reactive power into the grid to meet the following: (1) generation and load be in equilibrium at all times and (2) reduce the voltage fluctuations in power grid to prevent the damage of grid installations [28]. Fig. 11 shows the work flow of battery system. The battery management monitors the power from the wind turbines and controls the charge level of the batteries.

Applications. The hybrid energy storage ensures wind power to be fed into the grid always. On excess wind power generation, the hybrid storage system absorbs the excess and feeds it into the grid later. The renewable energy sources (causing strong fluctuations in supply) were integrated more effectively into the existing power grid. The wind-turbine power generation continues even when the grid is overloaded. The storage system helps to balance short-term fluctuations in load or in energy production. The lithium-ion batteries are high-power batteries that can

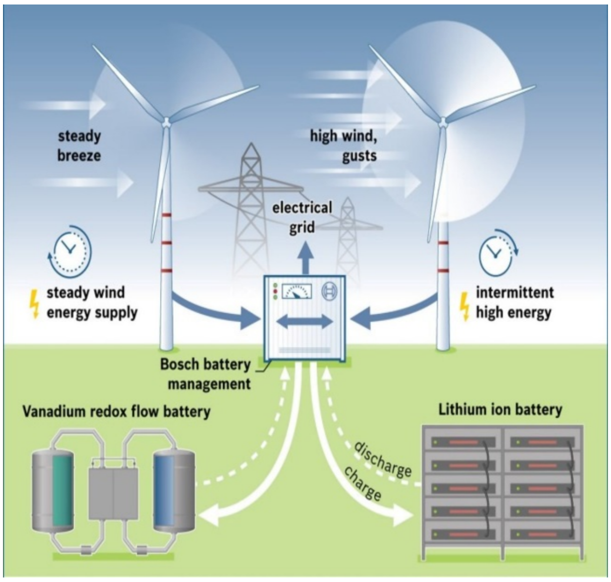


Fig. 11 High performance hybrid energy storage [28].

charge and discharge over a short period of time. On the other hand, vanadium redox flow or high-energy batteries store large amounts of energy very efficiently over long periods of time. Using both the technologies makes the energy storage facility balanced. This energy storage facility has resulted as an important milestone for supplying renewable energy in future. The advanced technology of the battery systems makes it easier to integrate renewable energy with the grid more efficiently [28].

3.1.4 Minami-Soma Substation—Tohoku Electric /Toshiba

Project Deployment. The project was deployed by the Tohoku Electric Power Company. The BESS was installed in a power transmission substation in Minami-Soma, on Japan's east coast in Fukushima prefecture, as a part of the Minami-Soma Substation Project. After the completion of the validation period the battery storage system became a part of Tohoku Electric Power in 2016 [30]. The large-capacity storage battery system was constructed on an unused plot with about 8,500 m^2 of land area. The battery energy system is connected to a 189 MW solar power plant. Fukushima Green Power Project is financed by Fukushima Prefecture and other entities [31].

Battery Technology. This project uses 40 MW-40 MWh lithium-ion battery. Each cell of the Li-ion battery has a capacity of 2.3 V, 23 Ah. Each battery module is composed of 24 cells, and the storage battery panel has 22 built-in modules. The 26 storage battery panels are stored in each of the storage battery containers as shown in Fig. 12. Toshiba Corporation supplied the BESS, the transformers for connections to grid, step-up transformers, power conditioner, battery panels and battery modules. The bidirectional power conditioner for the storage batteries was manufactured by Toshiba Mitsubishi-Electric Industrial Systems Corp (TMEIC). Fig. 13 shows the entire area of the large storage battery system consisting of 120 containers, 20 step-up transformers and other equipment [31].

Fig. 12 Each container houses 26 storage battery panels [31].

Fig. 13 Power conditioners and step-up transformers are arranged between the storage batteries lined up on both sides [31].

Solar Power Plant. The solar power plant was constructed by Fukushima Green Power Project of Fukushima City and became operational in December 2015. The solar power plant has 7,700 solar panels manufactured by Trina Solar Ltd. It is mounted on about 3.2 ha of agricultural land. The PV inverter of the solar panels is obtained from TMEIC. Fig. 14 shows the solar power plant. The solar power plant is connected to Tohoku electric power [32].

Fig. 14 The "Okuma Town Furusato Revitalization Mega Solar Power Plant" is connected to the grid in the Minami-Soma storage battery preferential access frame [32].

Power Electronics. The power conditioners were supplied by Toshiba. The output of the storage battery is 500 V DC. The 500 V DC is converted to 300 V AC by the power conditioners. The 20 step up transformers are used to boost up the voltage from 300 V AC to 6,000 V AC. The main transformer further boosts the voltage up to 66 kV before getting connected to the extra-high voltage power line. The power conditioners control the bidirectional power flow in the battery. By using a multiple-unit control panel, power conditioners control battery charge and discharge. The control command for the multiple control units is sent by the central load dispatching center of Tohoku Electric Power. The state of the batteries is monitored and controlled by Haramachi Technical Centre Control Station [33].

Applications. Some of the applications of the project include verifying the improvement of supply demand balance of the power grid, reducing voltage fluctuation, and regulating frequency fluctuations in the substation by using a large capacity battery energy storage system. The battery system is charged during excessive power output from the renewable energy and discharged during excessive demand, thereby balancing the supply and demand of power in the subsystem. The reactive power control of the storage battery system is utilized to reduce the voltage fluctuations in the local grid [31].

3.1.5 AES KilrootAdvancion® Energy Storage Array

Project Deployment. The governments of Ireland and Northern Ireland have a target to reach 40% renewable energy generation of their total electricity generation by 2020. As part of this improvement BESS is deployed in Northern Ireland's Kilroot power station [34]. The KilrootAdvancion® energy storage (AES) array project is operated by AES Corporation. This is the first transmission grid scale array in the United Kingdom. The Kilroot power station is located at Northern Ireland, UK. AES operates the 10 MW/5 MWh energy storage system deployed in Kilroot coal fired generation power plant [35]. The energy storage system is connected to the System Operator of Northern Ireland (SONI) part of EirGrid Group. A significant amount of renewable generation most of which is onshore wind is connected to the transmission grid. The storage project is associated with AES, Queen's University Belfast, SONI, Northern Ireland Electricity (NIE) and the Utility Regulator [36]. The construction of the energy storage project started on July 1, 2015 and was available for service on January 5, 2016 [37]. The project is mainly funded by Federal/Nation grant [35].

Battery Technology. This project utilizes fourth generation Lithium-ion battery technology by AES [37]. The energy storage array has 53,000 battery units. Fig. 15 shows the battery array in Kilroot power station. The rated power for the energy storage is 10 MW [36]. The inverters are supplied by Parkar Hannifin. The battery storage system has its full output available at a 1% deviation from nominal frequency. The battery outputs if there is a +/-0.5 Hz frequency deviation operating at a nominal frequency of 50 Hz. The battery is held at 70% during normal operation. The low frequency events discharge the battery and in high frequency events battery draw

Fig. 15 The 10-MW Kilroot Array was installed inside an unused turbine hall in the Kilroot Power Station and is integrated into the station's electrical infrastructure [36].

charge from grid. The battery can supply 10 MW of generation to the grid at an emergency [34].

Wind Technology. Northern Ireland grid system has many wind farms contributing about 600 MW of wind energy production [34]. Wind energy has satisfied 20% of the north's electricity needs in 2015. On June 1, 2015, 583 MW of energy was provided by wind which is about 48% of the Northern Ireland's electricity. The wind farms are scattered all over Northern Ireland. Due to good wind profile, wind farms are growing rapidly in the region [37].

Power Electronics. Parker Company provided the inverter for the 10 MW AES KilrootAdvancion® Energy Storage Array [38]. The bidirectional inverter converts AC power from the grid to DC power while charging the battery and converts stored DC power to AC power while discharging. It synchronizes with grid frequency and voltage providing stable power output. It can respond to correct short term frequency and voltage fluctuations [39].

Applications. The supply and demand of the electricity in the grid is balanced by Kilroot storage array. It supports the all Island transmission grid via SONI. The Advancion array helps to integrate renewable power sources, improves power supply, and enables more efficient transmission of existing generation. The storage array helps to maintain the stability and reliability of the grid and also to reduce the energy cost for the consumers [36].

3.1.6 Grand Ridge Energy Storage 31.5 MW

Project Deployment. Invenergy's Grand Ridge Energy Storage project is in LaSalle County, Illinois approximately 80 miles southwest of Chicago [40]. Grand Ridge is one of the leading renewable energy centers and is the second-largest lithium-ion technology battery project in the world. The project began commercial operation in May, 2015. The project includes 210 MW wind farm, 20 MW solar project, 31.5 MW storage unit and another 1.5 MW energy storage project [41]. Fig. 16 shows the project site in Grand Ridge.

Battery Technology. The project uses 32 MW lithium iron phosphate battery technology. The energy storage is provided by BYD America. Fig. 17 shows BYD America's containerized energy storage. The project consists of 22 identical energy storage modular units. Each modular unit consists of thousands of individual battery cells, power conditioning equipment, safety and monitoring systems. RES Americas provided the control and dispatch systems for the energy storage. This interrelated approach significantly improves the system dependability and increases the simplicity of the project's construction and process [42].

Wind Turbine Technology. The wind farm of the Grand Ridge is built in 4 phases. The first phase includes 66 wind turbines from GE Energy with diameter and hub height of 77 m and 80 m respectively. The nominal power rating for the wind farm is 99,000 kW (commissioned from 2008) [43]. The second phase includes 34 turbines from GE with same configuration. The total nominal power is 51,000 kW (commissioned from 2009) [44]. Phase three and phase four each includes 20 GE wind turbines with same configuration. The total nominal power is 60,000 kW (both the phases are commissioned from 2009) [45, 46].

Fig. 16 Grand bidge project site Illinois [41].

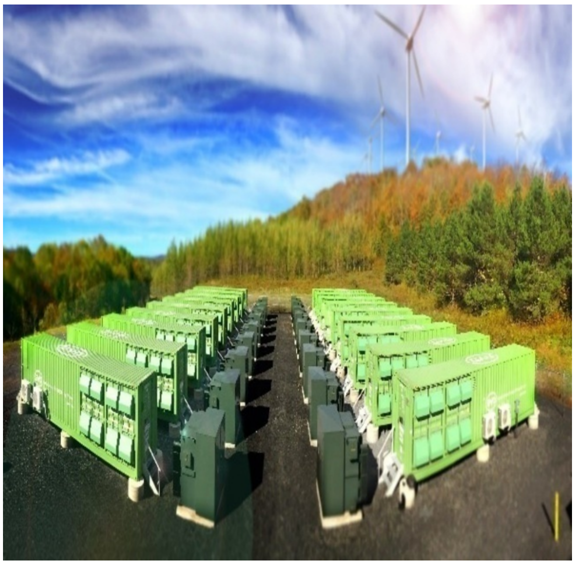


Fig. 17 BYD America's containerized energy storage [42].

Solar Project. The Blue Grand Ridge Solar Farm is located in the town of Streator, Illinois. To date this project is the largest solar farm built in the Midwest [47]. The total power is 23 MW. It consists of 20 individual 1 MW solar inverters and over 155,000 photovoltaic modules. The inverters, transformers, re-combiners and photovoltaic modules are supplied by General Electric [48]. GE also provides SunIQ plant controls which enhance the grid integration capability of the solar plant [49].

Applications. The Grand Ridge Energy Storage delivers fast-response regulation service to the huge

Fig. 18 WEICan's Wind Farm, PEI, Canada [59].

PJM market. PJM is a local transmission association that manages the movement of wholesale electricity in 13 US states and the District of Columbia. The Energy storage system absorbs and injects energy to manage grid disturbance due to renewable energy fluctuations. Large-scale batteries also support grid reliability by frequency regulation [50].

3.2 Sodium-nickel-chloride Battery Technology

Research Development

The sodium/nickel chloride batteries have a cathode of nickel (Ni) and salt (NaCl) and an anode of molten sodium (Na). Beta alumina is used as an electrolyte to conduct sodium ion [51]. The operating temperature range is 270-350 degree Celsius. The technology of sodium nickel chloride battery is also known as ZEBRA battery. The ZEBRA battery has moderate specific energy (94-120 Wh/kg), energy density (150 W h/L), and specific power (150-170 W/kg) [6, 8, 52-54]. The advantages consist of good pulse power capability, cell maintenance free and zero ambient emissions. Due to very little self-discharge, energy can be stored for long periods without the need of periodic recharge. It has zero memory effect and relatively high cycle life. It is suitable for distribution grids: peak shaving, smoothing & energy time shifting for renewable generation, micro-grid on-grid & off-grid applications [6, 55].

Current research focuses on improvement of specific power, increases the life cycle, lowers the operating temperature and reduces the cost of production. Using advanced additives to the positive active materials and by lowering the resistance of the solid ceramics electrolyte, the specific power is improved in Laboratory scale [56, 57]. The GE Durathon battery manufacturers and FIAMM energy storage solutions provide commercially available sodium nickel chloride batteries. Below are some of the projects that use sodium nickel chloride batteries.

3.2.1 Wind Energy Institute of Canada Durathon Battery

Project Deployment. Wind R&D Park and Storage project is led by Wind Energy institute of Canada (WEICan). The project is in Prince Edward Island (PEI). The total project cost is around $3M [58]. The project is funded with $12M from the Clean Energy Fund. A high percentage of the island's load is supplied by wind energy. The load of the province fluctuates from 90 to 260 MW. The wind energy generation also fluctuates depending on the availability of the wind. The intermittent generation of wind creates a constant mismatch between the supply and demand. To overcome this situation Wind Energy Institution of Canada along with its partners, Maritime Electric Company Limited (MECL), New Brunswick Transmission and System Operator (T&SO), Canadian Wind Energy Association (CanWEA), and the PEI Energy Corporation (PEIEC) started the storage project. The project is deployed to gain knowledge on the impact of energy storage when connected with a wind farm. The project emphasizes on advance wind turbine technology and overcoming issues with grid integration with renewable energies. The project is collaborated with 10 MW wind park. The information gathered from the project is used for efficient grid integration with renewable energies in future [59].

Fig. 19 Battery storage unit and a wind turbine in WEICan's battery project site, PEI, Canada [58].

Battery Technology. This project uses 1 MW sodium-nickel-chloride battery. The Battery system is integrated with the 10 MW Wind R&D Park [58]. The BESS was put into operation in February of 2014. The BESS includes two components: a power conversion system and battery modules. The power conversion system is supplied by S&C Electric Canada Ltd. (S&C). The battery modules are supplied by GE. The batteries are based on GE's sodium nickel chloride Durathon modules [59]. The GE Durathon Battery has long float life and provides high energy density without using harmful materials [60]. Fig. 19 shows the battery storage system in the project site.

Wind Turbine Technology. Wind Energy institution of Canada has five 2 MW DeWind D9.2 turbines. The turbines were installed on 38-acre land of the institution site in North Cape, PEI. The turbines have synchronous generator that helps to maintain grid stability by providing inertia to the electric grid. The turbines are also capable of supporting the grid in the electrical network when voltage dip occurs. The turbines were commissioned in April 2013 [59].

Power Electronics. The power conversion system in the BESS is maintained using PureWave SMS converters. The BESS was operating on time-shifting mode for the first seven months. In time shifting mode battery is charged at night time due to high prediction of wind at night time and discharged at peak hours in the evening. The wind turbine consumes reactive power thus maintaining the system voltage. The integration potential of wind power into the grid increased and the grid became more reliable as the turbines can operate at a high capacity factor [59].

Applications. The main application of this project is to gather knowledge on effective integration of wind energy and battery storage. The energy storage system is used to compensate the power output oscillation due to wind speed fluctuation. The electricity storage enhances the advantage of wind power integration into the electrical grid. The local demand controller, utility scale wind and storage system are combined in the project to demonstrate the advantages of such integration. The project will help to validate the example of small turbines from various suppliers, expedite the dependability and performance of small wind systems, and consolidate scientists and suppliers of wind forecasting systems to improve wind predictions [61].

3.2.2 Gasfinolhu Island Resort

Project Deployment. Gasfinolhu Island resort is the first ecological and sustainable luxury resort in the world, located in an island in Maldives. The resort situated about 25 minutes from Male (by speedboat), features 52 rooms, including 30 overwater bungalows, all of which run on the solar power produced on the island. It has a micro grid hybrid energy system with batteries, inverters, photovoltaic panels, and thermic solar panels. The Gasfinolhu Island Resort is fully self-sufficient in all aspects and fully environment friendly. The complex overall system of the resort is designed by Japanese architect Yuji Yamazaki. It is valued more than 45 million dollars. The project comprises of supply networks, reverse osmosis for drinkable water, sewerage, hot water production, and the micro grid hybrid energy system [62, 63].

Battery Technology. The battery technology used for the project is sodium nickel with integrated battery management system consisting of 64 batteries. Each battery has energy of 23.5 kWh with total voltage of the battery as 620 V. The energy storage technology is provided by FIAMM SoNik. Nidec ASI provided the power electronics. The entire system is monitored constantly from Italy by T&D technicians. The power management system is used to manage and control the system [62].

Solar Technology. The Island has 6,500 m^2 of solar panels with a total capacity of 1,100 kW. At peak load island's full occupancy requires 600 kW. The solar panels are situated on the arrival jetty and adorn the rooftops of utility buildings shown in Fig. 20. The Island's solar power system required an investment of 8 million US dollars. The cost of the system is expected to be recovered within seven or eight years [64].

Fig. 20 Rooftop solar panels [64].

Power Electronics. The power system of the resort is completely computerized with computers encoded to shift between direct solar power, battery power, or diesel generators (if required). The power management system (PMS) controls the resort's power system. Fig. 21 shows the monitoring of PMS. It has power conversions system controller, system protection, battery charging and discharging management and adjustment system, software for monitoring and event recording. The BESS works as a load which uses the excess energy produced by the PV system to charge the batteries. At night, the resort is powered by the stored energy from the battery. The island also has diesel generator for emergencies (in case of successive rainy days and the batteries run out) [63].

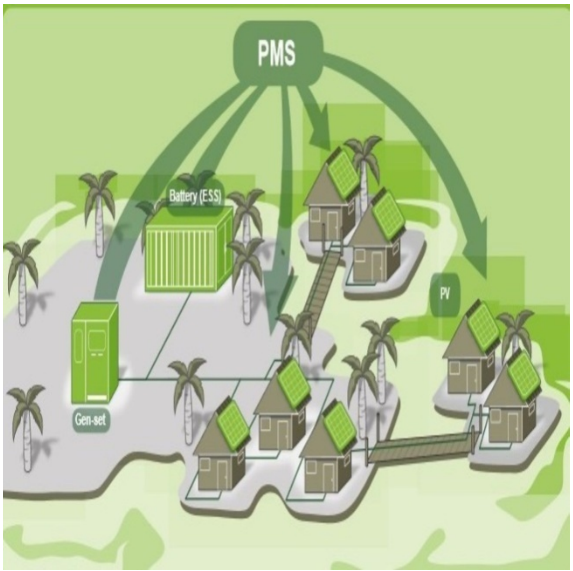


Fig. 21 Power management system monitoring diagram of the resort [65].

Applications. The Gasfinolhu Island resort is a solar powered resort saving CO_2 emissions in the environment. The energy storage device ensures stability of the electric network. Being able to store energy, battery storage systems help to promote local generation of energy, particularly from the renewable energy sources such as small-scale wind and solar. Micro grid controller system helps to maintain grid stability and full electric functionality of the resort by focusing on maximizing the energy from the installed solar panels [65].

3.3 Lead Acid Battery

Research Development

The lead-acid battery uses lead oxide (PbO_2) as cathode and lead (Pb) as anode and the electrolyte is sulfuric acid. They have an energy density of 50-90 Wh/L, specific energy of 30-50 Wh/kg and specific power of 75-250 W/kg [6, 8, 11, 67]. Due to its fast response time it has been used in grid applications for frequency regulation. Also the daily discharge rate is low and has a low capital cost.

The research and development of lead-acid batteries focuses on: (1) increasing batteries specific energy and energy density. Researchers are focusing on different materials and cell design for performance improvement such as extending cycling life and enhancing the deep discharge capability; (2) implementing the battery technology for applications in the wind, photovoltaic power integration and automotive sectors [68-70].

3.3.1 Pillar Mountain Wind Project—Xtreme Power

Project Deployment. The Kodiak Island in Alaska has wind farms which contribute almost 99% of the total energy consumption. The energy storage system is deployed in the site to act as a bridge between supply and demand mismatch. A 3 MW advanced lead-acid energy storage system has been deployed in Kodiak Island [71]. The entire system integrates wind-hydropower and diesel system at Pillar Mountain. Alaska has a goal to achieve 50% of their electricity production from renewable energy by 2025. Kodiak Island has almost 100% of their power generation from renewable energy sources [72]. The project was completed by the end of 2014, and enabled the community of Pillar Mountain to satisfy 99.7% of its energy needs from renewable energy sources. The town utilizes the diesel generators only as a back-up, thus saving 7,255,345 gallons of diesel since 2009. The hybrid system in Kodiak blends wind, diesel and hydropower. It is also combined with the Terror Lake hydroelectric project that makes the Kodiak Electric Association (KEA) to shut off their diesel generators almost all year [71].

Battery Technology. Xtreme power supplied the advanced lead acid battery for the project. Fig. 23 shows containers housing the 3 MW / 0.75 MWh batteries on Kodiak. Lead-acid battery storage system remains at a high state of charge and can discharge

Fig. 22 Two containers housing the 3 MW / 0.75 MWh battery park on Kodiak [72].

Fig. 23 Wind turbines at Kodiak Island, Alaska [71].

quickly for very short periods. One of the most important operating conditions is temperature. The inside of the container is always maintained at 20-30 ^{o}C. For an enhanced performance the project developers are planning to upgrade the energy storage system to lithium ion technology [73].

Wind Turbine. The first stage of the project consists of installing three 1.5 MW General Electric turbines and integrating them into the hydropower system together on an isolated grid at a cost of approximately

$21 million. Fig. 23 shows the wind turbines at Kodiak Island. The project was financed by KEA with a fund from Alaska Energy Authority and additional clean renewable energy bonds (CREBs). After a successful first phase, KEA doubled the wind capacity by installing additional three megawatt turbines. The installation was completed in the fall of 2012. Combined, the six wind turbines produced 9 MW of wind power [73].

Power Electronics. The project deployed a Younicos Energy Storage System (ESS). Each advanced lead-acid energy storage has a power conversion systems (PCS) attached with it [74]. The grid condition is measured 100 times per second and if the grid frequency drops below 59.8 Hz, ESS immediately supplies up to 3 MW of real power within 50 milliseconds. The system can supply highest power of 4.5 MW for 30 seconds with 150% overload capability. Throughout the years KEA has sustained their outstanding history of confirming grid stability while maximizing use of the island's substantial wind energy [72].

Applications. The project was commissioned in November 2012. Since then the Younicos ESS has effectively responded to an average of approximately 165 events per day in total over 253,000 frequency events. Due to this fast-acting, accurate response during sudden drops in grid frequency, the ESS has assisted to avoid several impending power losses and in some cases prohibited island-wide blackout. The ESS helped to limit the diesel fuel consumption and allowed KEA to take complete benefit of the 9 MW wind capacity. KEA has supplied 114 million kWh of wind energy [72].

3.4 Zinc Bromide Flow battery

Research Development

The Zinc bromide battery is a hybrid flow battery. The Zinc bromide solution is stored in two tanks: the solution flow through a reactor stack and back into the tank during charging and discharging. Carbon plastic electrodes are used in compartments as the reactor stack [6, 75]. The energy density ranges from 34.4-54 W.h/kg and specific energy ranges from 34.4-54 W.h/kg. It has relatively high energy density at low cost which makes it suitable for large scale energy storage system for grid applications [75]. It also has high (100%) depth of discharge capability on a daily basis and is non-perishable which gives it no shelf life limitation.

Recent research focuses on increasing the power density and energy efficiency of the battery [6, 76, 77]. Investigation is being done to increase the electrolyte conductivity to increase the power density. There are different companies providing commercially available zinc bromide batteries such as Primus Power—Hayward, California, USA; RedFlow Limited—Brisbane, Australia; Smart Energy—Shanghai, China; ZBB Energy Corporation—Menomonee Falls, Wisconsin, USA; and ZBEST Power—Beijing, China [75].

3.4.1 RedFlow 300 kW Adelaide

Project Deployment. Base64 is an office complex built around historic Adelaide mansion in Adelaide, Australia. Base64 has deployed a commercial-scale zinc bromide flow energy storage system to couple it with an existing solar array. The BESS is developed by pioneering Brisbane-based energy storage company Redflow, with a budget of $1 million. The battery energy system is scalable and can be positioned in series and/or parallel to be driven from renewable energy sources such as solar. The long term plan for base64 office complex is to take the office off-grid. The BESS stores energy from the existing 20 kW array of solar panels [78].

Battery Technology. The battery system deployed in Base64 is a large-Scale battery (LSB) unit that can be charged from solar. It is worth about $730,000 (US $550,000) and was delivered fully assembled. The LSB can deliver a 200-kW continuous energy with a 300-kW peak and includes full system control and monitoring hardware within the unit [79]. The BESS is contained in a 20-foot (6 m) box with 60

REDFLOW ZBM3 battery modules. Each module has an energy of 11 kWh in total storage capacity of 660 kWh. The voltage range is between 400 V and 800 V DC. The BESS can provide at least four days of continuous energy supply [80]. The BESS significantly reduces Base64's need for grid energy and associated carbon emissions [79].

Solar Technology. Base64 has an array of 80 PV solar panels with a capacity of 20 kW. Another 50-kW solar PV is going to be installed in Base64 to provide an enormous degree of energy independence [79]. Fig. 24 shows the rooftop solar panels.

Power Electronics. ABB's Power Conversion System (PCS) having 100 inverters system is used to interface the BESS into Base64's three-phase energy feed. PCS is highly efficient and precisely intended to resolve power quality problems and stabilize networks. The power converter provides reliable and cost-effective performance [81].

Applications. The BESS allows time-shift of the energy produced by the solar PV. It makes the Base64 self-sufficient in energy production and consumption. The system works as a massive uninterruptible power supply (UPS) to protect business-critical systems from brown outs and power outages [82, 83].

Fig. 24 Rooftop solar panels [79].

Table 1 Summary of the battery energy storage projects around the world.

Project name	Site location	Renewable source integration	Battery technology				
			Battery type	Provider	Energy	Control technology provider	Application
Zhangbei National Wind and Solar Energy Storage and Transmission Demonstration Project [14]	Zhangbei, Hebei China	100 MW (wind) 40 MW (solar)	Lithium ion	BYD, Amperex technology Ltd. (ATL), China Aviation Lithium Battery Co. Ltd. , Wanxiang Group	36 MWh, 16 MW, 9 MWh, 2 MWh	BYD Soaring, XJ Group, Sifang	Electric energy time shift Frequency regulation Ramping Renewables capacity Firming Voltage support
			Vanadium redox flow battery	Prudent Energy	8 MWh	ABB	Frequency regulation Ramping Renewables capacity Firming
Wind and Storage Demonstration in a First Nations Community [21, 22, 26]	Saskatchewan, Canada	800 kW wind turbine	Lithium ion	Saft technology's Itensium Max 20E battery systems	740 KWh	ABB's EssProPower Conversion System (PCS)	Fast response, respond to changes of wind within less than one second.
Bosch Braderup Energy Storage (ES) Facility [27, 28]	North Sea coast, Schleswig-Holstein, Germany	18 MW Wind	Lithium ion	Sony	2 MWh	Bosch	High-power batteries that can charge and discharge over a short period of time [28]
			Vanadium Redox Flow Battery	Vanadis Power GmbH	1 MWh	Bosch	High-energy batteries store large amounts of energy very efficiently over long periods of time

Table 1 to be continued

Minami-Soma Substation—Tohoku Electric/Toshiba [31]	Minami-Soma	Solar panels	Lithium Ion	Toshiba Corporation	40 MWh	Toshiba Mitsubishi-Electric Industrial Systems Corp (TMEIC)	Renewables capacity Firming Renewables energy time Shift
AES KilrootAdvancion Energy Storage Array [34, 36]	Northern Ireland's Kilroot power station	600 MW wind	Lithium ion	AES's AES KilrootAdvancion® Energy Storage Array	10 MW	Parker Company	Frequency regulation
Grand Ridge Energy Storage [41, 50]	LaSalle County, Illinois	210 MW wind farm, 20 MW solar project	Lithiun Ion	BYD America	32 MW	RES Americas	Frequency regulation
Wind Energy Institute of Canada Durathon Battery [59, 61]	Prince Edward Island (PEI)	2 MW wind	sodium nickel chloride Durathon module	GE and power conversions system by S&C Electric Canada Ltd. (S&C)	1 MW	PureWave SMS converters	compensate the power output oscillation due to wind speed fluctuation, Local load demand control
Gasfinolhu Island Resort [62, 63, 65]	Maldives	1,100 kW solar	Sodium-nickel-chloride	FIAMM SoNik	1.5 MWh	Nidec ASI	Load demand control
Pillar Mountain Wind Project—Xtreme Power [71, 72]	Kodiak Island in Alaska	1.5 MW wind	Lead Acid Battery	Xtreme power	3 MW	Xtreme power	Frequency regulation
RedFlow 300 kW Adelaide [78, 79, 81-83]	Adelaide mansion in Adelaide, Australia	20 kW PV solar panels	Zinc Bromide Flow battery	RedFlow Limited - Brisbane, Australia	660 kWh	ABB's Power Conversion System (PCS)	uninterruptible power supply (UPS)

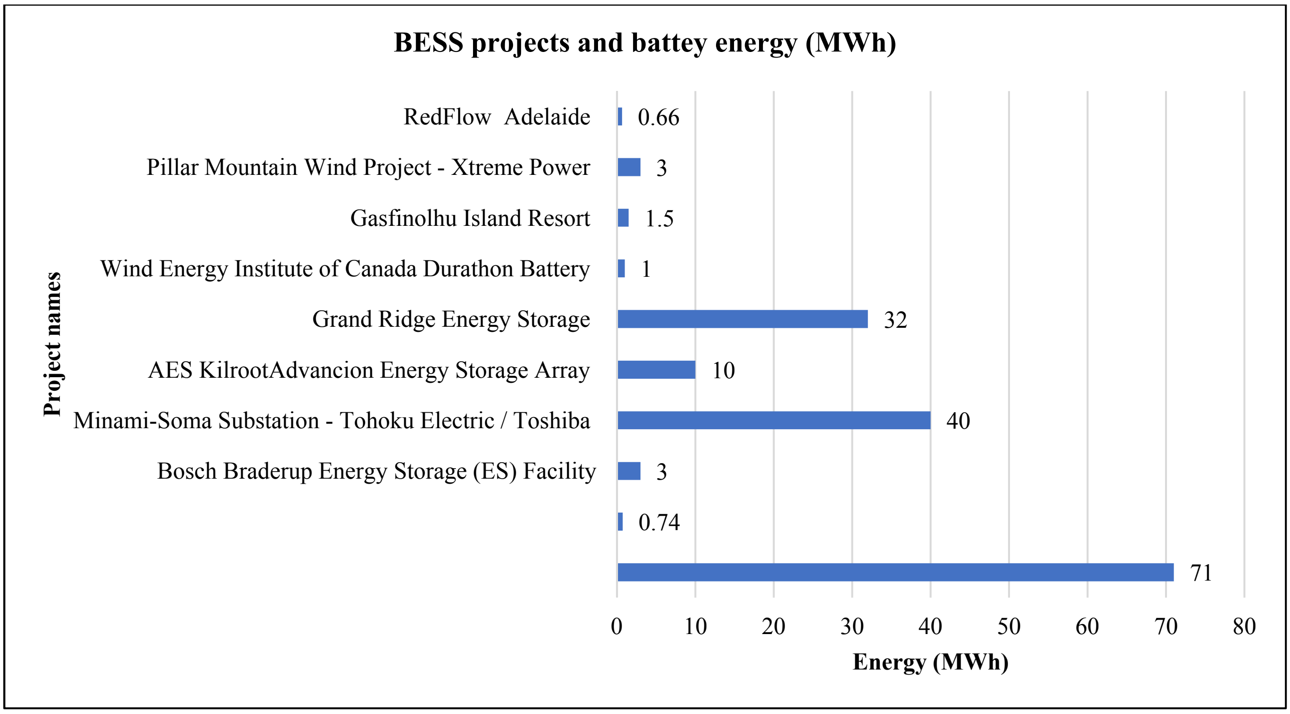


Fig. 25 Battery energy projects and their battery energy.

Table 2 Technical characteristics of battery technologies.

Battery technology	Lifetime (years)	Specific energy (W h/kg)	Specific power (W/kg)	Response time	Advantages	Drawbacks
Li-ion [6, 8, 66, 84, 85]	5– 15	75-200 [8]	150-315	Milliseconds, <1/4 cycle	High energy density, low self-discharge, Zero to low memory effect, Quick charging, Longer lifespan	Expensive, protection required, ageing
Sodium Nickel Chloride [86-90]	5-8	90	150	Milliseconds	Superior battery safety, high open circuit voltage, lower operating temperature, remote monitoring, long maintenance-free storage period	High capital cost, high intrinsic resistance , high production cycle time
Lead Acid Battery [6, 8, 91-95]	5-15	30-50	75-300	<1/4 cycle milliseconds	Tolerant to overcharging, low internal impedance, can deliver high current, wide range of sizes and capacities available, 100% recyclable. Inexpensive to manufacture	Low specific energy, relatively low cycling time and energy density, must be stored in charged condition in order to prevent sulfation
Zinc Bromide Flow Battery [6, 8, 91, 96, 97, 99-101]	5-10	30-50	100	<1/4 cycle	Low cost production and from readily available materials, Good specific energy and energy efficiency, recyclable, Ambient temperature operation, 100% depth of discharge rate	Needs to be fully discharged every few days, Low areal power (<0.2 W/cm^2)

4. Conclusions

Renewable energy integration into the grid has always been a challenge for the grid operators. The energy storage system has become essential to balance the supply and demand of electricity. The intermittent nature of renewable energy increases the need for energy storage system to balance the system and restore the system loss and increase the reliability. The paper presents a comprehensive review on the grid connected battery projects which are deployed to address some of the applications such as reducing the distribution and transmission losses, maintaining the voltage level, and increasing the reliability of the grid (as summarized in Table 1). Fig. 25 shows the different battery energy projects and the capacity of their batteries. The advantages and disadvantages of each battery technology have also been described here (as summarized in Table 2). Different companies are building grid scale storage batteries that require control technologies. It is observed that lithium-ion technology is the mostly used one due to its high energy density. Other than lithium-ion, lead acid technology, nickel iron, redox flow and sodium Sulphur batteries have also been used in few projects. Many other projects have incorporated multiple technology batteries to obtain the advantages of each technology. However there are drawbacks and difficulties associated with battery energy storage system such as low energy density, high cost of energy storage, system complexity, less life time, and cost compared to conventional generation systems. Research is being conducted to improve this emerging technology and to make it cost effective.

Conflict of Interest

The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; and in the decision to publish the results.

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