

Energy Storage in Microgrids

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I. INTRODUCTION

Driven by the global environmental emission issues, energy access in remote communities, and tighter requirements for system resiliency and reliability, electricity production is shifting its focus from a centralized paradigm to a decentralized one. In this context, renewable energy sources (RES) have proliferated in the last decade, with a steadily increasing trend. Thus, today, a large number of wind turbines and photovoltaic panels (PV) are connected to the medium (1-69 kV) and low-voltage (≤ 1 kV) grid, with traditional integrated bulk power systems becoming decentralized in the presence of active distribution networks, where the flow of power is bi-directional between generators and “prosumers”. In particular, with decreasing RES costs, these technologies are becoming attractive solutions to bring energy to remote communities and/or replace expensive fossil-fuel-based generators. However, RES such as wind and solar are intermittent sources of energy, difficult to predict, experiencing large output fluctuations, thus significantly affecting system voltage and frequency.

Microgrids are considered a critical link in the evolution from vertically integrated bulk power systems to a set of smart decentralized distribution networks. These are defined as a cluster of interconnected distributed energy resources (DERs), which include ESS and loads, and operate as a part of the grid or in an islanded/isolated mode. Microgrids are characterized by a high penetration of RES, easily scalable structures, and increased reliability levels. However, microgrid operation has certain challenges, especially with high RES penetration, given their intermittent nature. In addition, most of the DERs in microgrids are connected through inverters, reducing the mechanical inertia in the system. As a result, microgrids face a problem of maintaining a stable and optimal operation. In this context, ESS are a key enabling element for the operation of microgrids, as they compensate for generation and demand fluctuations, while providing various ancillary services, particularly frequency control.

Prior to the 1980s, storing electrical energy was significantly costly and inefficient, and had no market demand. Today, ESS are attracting considerable attention and investment, with microgrids creating a large market for them, as high-power and economically feasible power electronic systems have made storing electrical energy financially and technologically viable. Thus, ESS utilization in various microgrid sectors shows a considerable increase over the past year; for example, the commercial and

industrial sector utilization has more than tripled, as illustrated in Figure 1. There is a wide deployment of various ESS technologies in microgrids, such as Battery and Flow Battery ESS (BESS and FBESS), Flywheel ESS (FESS) and Fuel Cell and Hydrogen-based ESS (HFCESS). Thermal ESS (TESS) can also be a part of ESS, and are a cheaper option than other ESS technologies, and can be controlled to meet the thermal heating/cooling demand. With the high functionality of ESS along with the decreasing costs of these technologies, they are expected to become a key component of microgrids in the future.

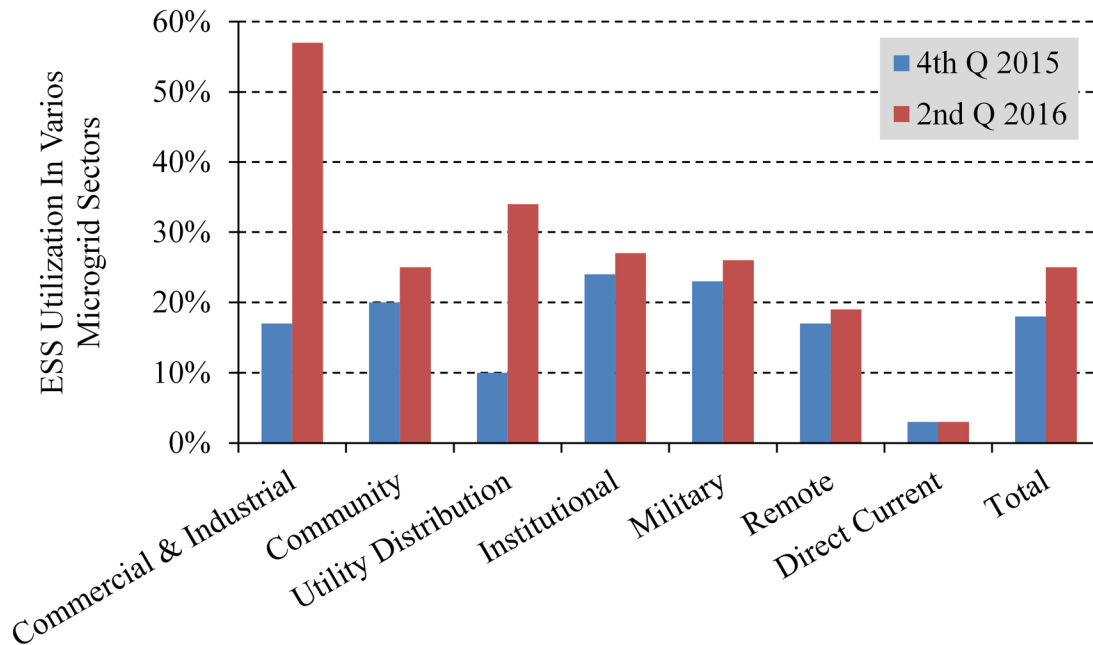


Fig. 1. Global ESS utilization by microgrid sectors (based on "Microgrid Deployment Tracker 2Q16", Navigant Research, 2nd quarter 2016).

This article focuses on ESS technologies and applications relevant to microgrids. Thus, the types of ESS technologies typically used in microgrids are described in some detail first, followed by several practical applications of ESS in isolated microgrids, which is where these systems are most necessary.

II. ESS TECHNOLOGIES

Depending on the functionality, technical, and economical criteria, various ESS technologies have been developed and used in microgrids. These technologies can be classified according to the forms of energy used, as shown in Figure 2, with Pumped-Hydro Storage (PHS) and Compressed Air Energy Storage (CAES) being limited to certain geographical areas and mostly to interconnected grids, while super-capacitors and superconducting magnetic coils are expensive and not widely used, therefore these technologies are not discussed in this article.

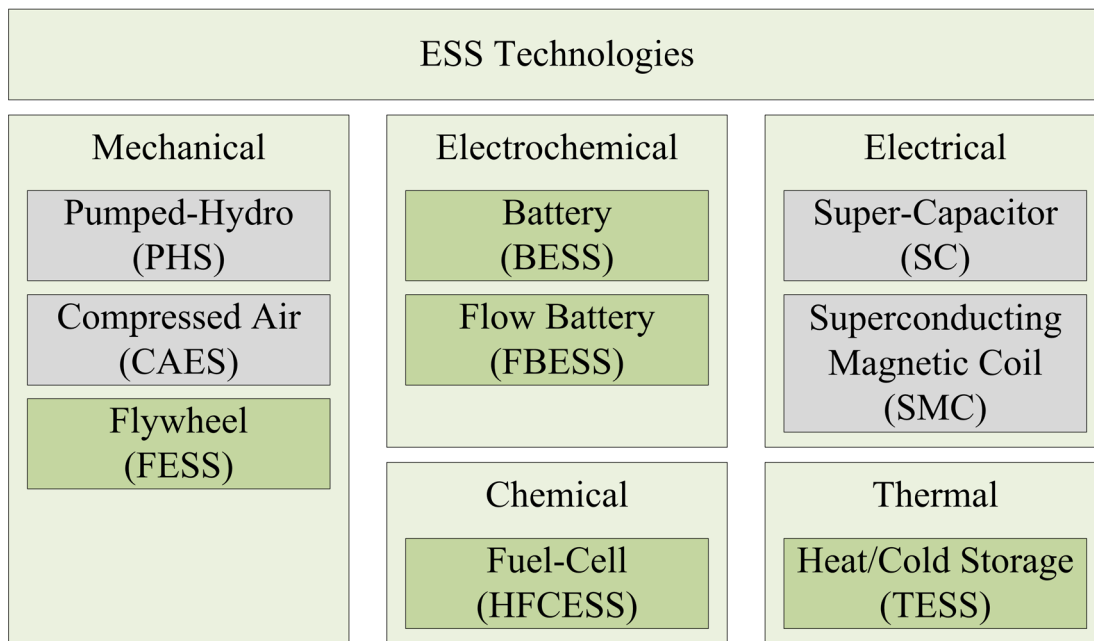


Fig. 2. ESS technologies classification (based on “Electrical Energy Storage”, white paper, IEC, Dec. 2011).

A. BESS

In BESS, the electrical energy is transformed and stored in form of chemical energy through an electrochemical process. A typical BESS consists of the battery cell, a dc/dc converter, and a dc/ac inverter. The electrochemical process takes place within the battery cell, where the electrolyte provides a medium for the anode and cathode to exchange positive and negative ions. The dc/dc converter along with the dc/ac inverter form the Power Conditioning System (PCS), which maintains the dc-link voltage and regulates the active and reactive power injection/absorption of the BESS.

A wide range of technologies exist in the fabrication of the battery cell, including lead-acid, nickel-cadmium, zinc-air, lithium-ion, etc. BESS are among the most widely developed and used types of ESS, since they are fast-responsive, highly efficient, have no harmful emissions, and require relatively low maintenance due to the absence of mechanical parts. On the other hand, these technologies are costly, and have a shorter life-span compared to other types of ESS, especially when used for high cycling applications, such as primary regulation.

The lithium-ion is among the most adopted battery technology in BESS. These have higher cell voltages compared to other battery technologies, which means that the required number of series cells to create a certain voltage level is lower. In addition, they have a high round-trip efficiency of around 95%-98%. State-of-the-art commercial lithium-ion batteries maintain an acceptable performance for up to 5000 cycles; however, their cost of ~\$1/Wh ranks them amongst the most expensive ESS technologies. Moreover, safety is an issue with these batteries, needing a thermal management system and protection equipment to prevent thermal runaways.

B. FBESS

A typical FBESS consists of flow cell stacks and at least one pair of tanks. The tanks contain the positive and negative liquid electrolyte; two closed-loop circuits connect the tanks to the flow cell stacks. Within each flow cell, an ion exchange membrane separates the positive and negative electrolyte; electrochemical active species are dissolved in the two electrolytes. The positive and the negative electrodes provide the surface area on which the electrochemical reaction takes place; thus, the energy is not stored in or around the anode and cathode, but in the electrolyte itself, with its volume determining the storage capacity of a flow battery. The charging and discharging power is determined by the size and the number of the flow cells. This decoupling of storage capacity and charging/discharging power is unique to FBESS, and makes these systems easily scalable.

FBESS are expected to handle more than 10,000 charging/discharging cycles over their life span. For large-scale mid-to-long-term storage, the cost of a flow battery depends on the cost of the electrolyte, and is expected to reduce with increasing production volume. The comparatively low round-trip efficiency of around 75-80% is one disadvantage of FBESS. In addition, FBESS have relatively low energy densities; the most common system, employing Vanadium in both electrolytes, yields an energy density of around 20 Wh/l. However, for stationary applications, such as those required in microgrids, this could be a minor drawback.

C. HFCESS

A typical HFCESS consists of a water electrolyzer, a hydrogen storage tank, and a fuel cell. In these systems, hydrogen is produced through an electrochemical process in the electrolyzer, during which the electric current splits a water molecule into hydrogen and oxygen. State-of-the art electrolyzers can produce high-pressure hydrogen of up to 6000 psi; the produced hydrogen can then be stored as gas in metal tanks, as liquid in low-temperature containers, or in metal and/or complex hydrides. However, in small islanded or remote microgrids, hydrogen is typically stored in above-ground gas bottles or tanks at pressures up to 900 psi. Note that the O_2 produced by the electrolysis process is not stored because of economic and technical issues.

Electricity is generated in an HFCESS through a reverse electrochemical reaction within the fuel-cell, during which the stored hydrogen reacts with the oxygen in the air, producing water and heat. Several technologies are used in fuel-cells, depending on the electrolytic material, such as alkaline and solid oxide fuel cells. Operating temperature, corrosion potential, and maintenance costs are among the decisive factors to choose the appropriate technology.

HFCESS offer several advantages, such as adequate dynamic response and no emissions, producing water as the by-product of the electrochemical reaction. These systems have a longer life-time compared to BESS, allowing up to 20,000 charge/discharge cycles; in addition, hydrogen can be stored for long periods. On the other hand, HFCESS have a considerably lower efficiency, with a net fuel-cell and electrolyzer efficiency of around 50%.

D. FESS

FESS store energy in the form of kinetic energy of a massive cylinder, spinning up to 50,000 rpm; the cylinder is coupled with an electric machine that acts as a motor during charge and as a generator during discharge. Friction and wind shear is reduced by using bearings and a vacuumed containment ring. In most cases, the permanent magnet electric machines are used in FESS, although it is also possible to use induction machines. The frequency of the electricity produced by the permanent magnet machines depends on the speed of rotation, thus electricity needs to be converted to dc and then back to ac before grid connection of the FESS.

FESS have a fast dynamic response, and are ideal for primary regulation provisions. However, they have a high self-discharge rate, around 20% of the nominal capacity per hour, which makes them inappropriate for long-term storage applications. Advantages of FESS include long life-span and cycling rate, high power and energy density, and high energy conversion efficiency.

E. TESS

TESS store thermal energy converted from electrical energy during off-peak hours and discharge that to meet the thermal demand. There are several kinds of TESS based on the storage medium, placement of storage, and the conversion of electric energy. The storage medium can be liquid or solid. The location of the storage can be directly in the room that is heated or cooled, or somewhere central to heat/cool the whole house or commercial building. These systems basically comprise three components: heating or cooling element, storage and heat exchanger, and air handling unit.

Brick-core electric thermal storage (ETS) systems are widely used as TESS for space heating in microgrids, in which the conversion of electric energy is carried out by heating rods that are placed between high-density bricks that store thermal energy; these bricks are in a well-insulated box to ensure a low self-discharge. To discharge the heat from the ETS, there is a controlled fan that blows air through the air channels in the bricks. For different room sizes of residential buildings, different sizes of brick core ETS systems are available, which differ in the electric power drawn and the thermal storage size. Standard room heating TESS are available in sizes ranging from 1.32 kW to 10.8 kW, 13.5 kWh to 40 kWh, while central house heating TESS are available in sizes ranging from 14 kW to 46.5 kW, and 120 to 240 kWh.

Ice-storage air conditioning systems are a type of TESS used for space cooling, in which the conversion of electric energy is carried out by a condenser that condenses the refrigerant. A heat exchanger made of copper coils is placed inside an insulated storage tank to circulate the refrigerant through the condenser, storage tank and the evaporated coil. The condensed refrigerant produces ice inside the storage tank during the charging, while the discharge takes place via an evaporating coil in the air handling unit. Residential or commercial cooling TESS are available in sizes of around 14 kW, with storage capacity ranging from 70 kWh to 105 kWh.

The charging of the TESS unit can be controlled locally by the user and/or centrally by grid operators using control signals. The cost of TESS range around 50-150 \$/kWh, which is comparatively much cheaper than BESS. The efficiency of TESS can be close to 100%. Because of their large storage capacity and rapid response rate, they can be used for frequency regulation, emergency support, coordination with RES, and load shifting.

III. APPLICATIONS

ESS play multiple roles in islanded/isolated microgrid with a high penetration of RES, providing ancillary services such as frequency and voltage regulation. In fossil-fuel-based microgrids, ESS can considerably reduce fuel consumption and the run-time of the generation assets, and for RES-based microgrids, they can ensure continuous and stable system operation. Figure 3 shows the frequency and duration of various services from ESS in the context of microgrids.

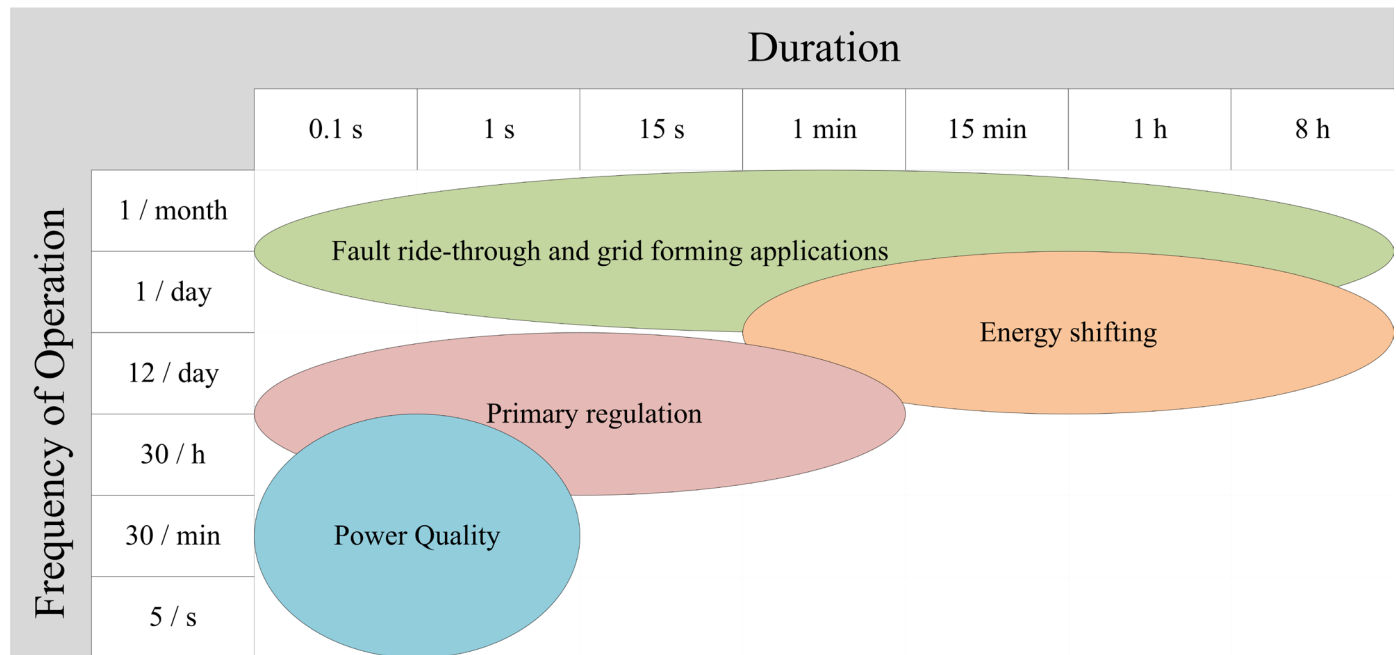


Fig.3. Time duration and frequency of operation of ESS in microgrids (based on “Electrical Energy Storage”, white paper, IEC, Dec. 2011).

Depending on the microgrid assets, size, and configuration, the control and dispatch of DERs, including ESS, can be either in decentralized local or centralized modes. To fully exploit all advantages offered by ESS, a centralized approach is preferable in industrial, commercial, and large residential microgrids, where a MicroGrid Central Controller (MGCC) controls and dispatches the assets. Existing communication architecture in microgrids are mainly based on wireless technologies that comply with IEEE 802.11 a/b, with the data being gathered and transmitted through ethernet. Figure 4 shows a schematic of a microgrid including ESS; note that in smaller microgrids supplied by one main RES, ESS could be connected to the dc-link of that RES to make it a dispatchable unit and thus save the cost of an extra dc/ac inverter.

A. Grid Forming

One core application of ESS is enabling an islanded/isolated microgrid to operate with no fossil-fuel-based generation, providing voltage and frequency for the system; such ESS are referred to as grid forming. ESS can smoothly transit to grid forming mode when required, providing synchronization for some DERs such as PV units, when the main microgrid source disconnects. Also, ESS enable seamless transition of a grid-connected microgrid to an islanded microgrid, allowing for its continuous operation of a microgrid during and after grid faults and outages. This is a key role for ESS in smart grids, since microgrids equipped with such ESS can mitigate the impact of grid outages. For example, in the aftermath of the super-storm Sandy, diesel-based backup generators could not operate since all gas stations were inoperable; hence, more than 1 GW of New Jersey's installed PV was unusable due to the absence of a voltage source. In this case, microgrids with grid forming ESS could have prevented the outage of PV units, providing continuous backup for critical loads.

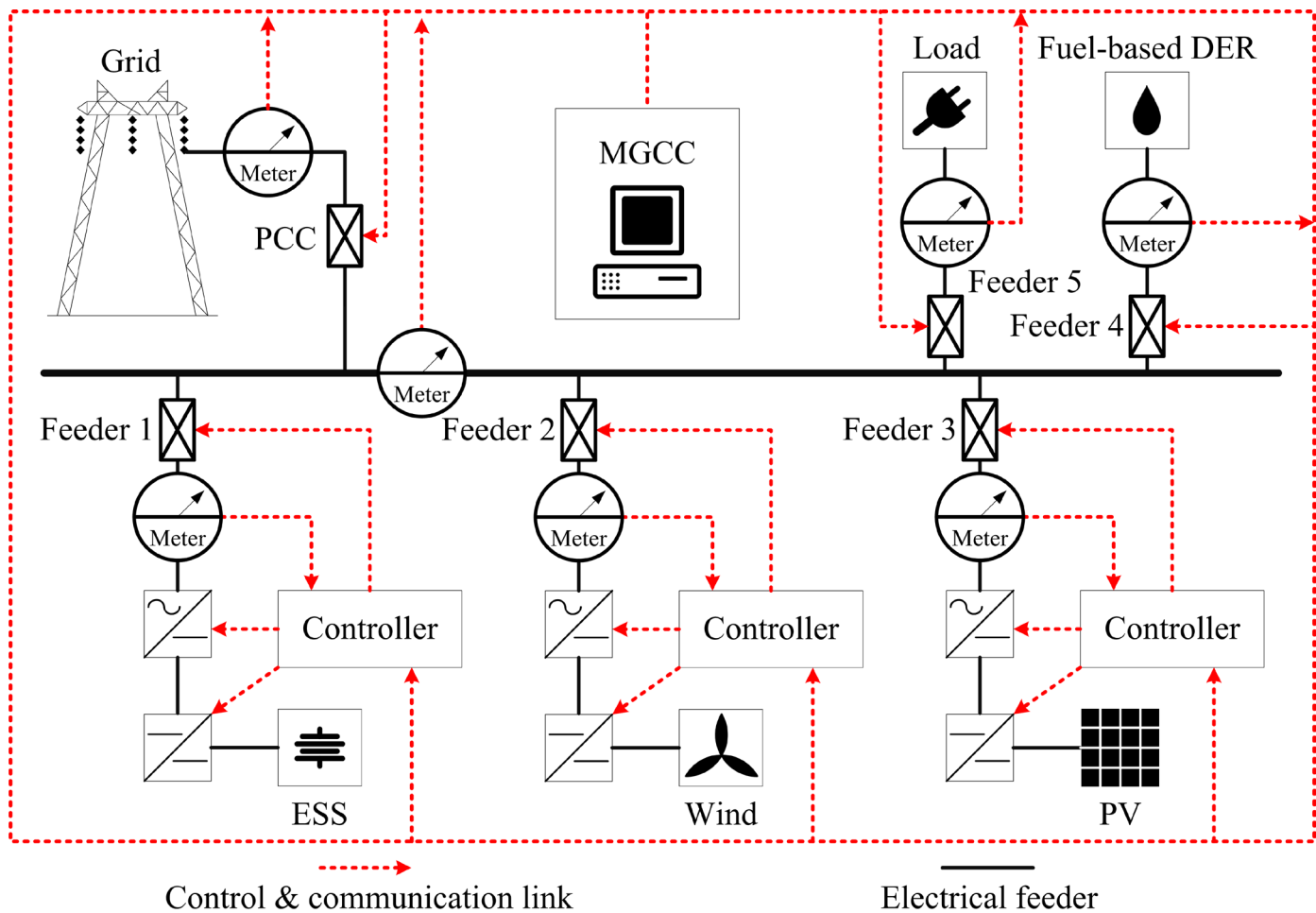


Fig. 4. Schematic of a centralized-controlled microgrid.

B. Voltage and Frequency Regulation

ESS can effectively compensate for the rapid output fluctuations in RES, mitigating the negative impact on system frequency and enhancing stability. Thus, frequency regulation is a critical task of ESS in islanded/isolated microgrids with a high share of

RES, since in such systems, PV units or wind turbines may experience large output fluctuations (up to 80% of their nominal power) in less than a few seconds, which can cause rapid frequency changes. For example, on December 22, 2005, the Danish Bornholm Island distribution system was isolated due to a failure in the high voltage transmission cables. During that period, local regulators were not able to compensate for fast variations of wind generator output powers, and as a result the whole distribution system was forced to shut down; high ramping-rate ESS such as FESS, BESS, and FBESS, could have prevented the problem. Specifically, FBESS are particularly suitable for such applications, due to their high cycling rate and overload capacity. Also, TESS which are commercially available as Grid-interactive Electric Thermal Storage (GETS), could be used in this case, as they can measure and respond to changes in the grid frequency by activating an appropriate number of heating elements to cope with rapid changes in RES generation.

ESS can also participate in voltage regulation and reactive power compensation in islanded/isolated microgrids. In industrial and commercial islanded microgrids, there might be large reactive power consumers such as industrial-size induction motors and/or electric furnaces. In such systems, fast-responsive ESS can considerably improve the power quality, effectively compensating for reactive power variations by regulating the system voltage.

ESS size and control techniques should be carefully chosen to ensure an acceptable power quality and guarantee the system stability. Thus, optimization techniques are usually utilized to minimize the investment, operation, and maintenance costs, considering security and reliability constraints.

C. Energy Shifting

ESS can be utilized to store the surplus energy and use it when needed. Such service is incentivized for various reasons, depending on the microgrid operating mode and DERs types. In off-grid systems fully supplied by RES, energy shifting is a critical application that ensures continuous operation. For such systems, careful planning is required in advance to determine the optimal capacity of the ESS based on historical data of solar irradiance and wind profiles, and electric loads.

In islanded/isolated microgrids that include fossil-fuel-based generation, ESS can be utilized to reduce the consumption of fuel and increase the efficiency of fuel-based generators. Thus, in such systems, appropriate optimization models can determine the optimal contribution of DERs, including ESS, to supply the demand at minimum operating cost. In standalone diesel-based microgrids, generators often operate inefficiently, some even suffering from low-load operation that causes wet-stacking and breakdowns. In this case, ESS can perform peak load shaving and valley filling to increase the efficiency of the generator and reduce the operating and maintenance costs. For larger microgrids where electricity market principles apply, peak shaving and valley filling services may be provided by ESS to store energy during off-peak hours when the electricity price is cheap, and inject it during periods of high electricity demand and price.

In all the aforementioned energy shifting scenarios, ESS are expected to have adequate capacity to supply the nominal load for

a few hours, depending on the load and RES supply profiles. Well-suited ESS technologies for these applications include BESS, FBESS, HFCESS, and TESS; note that TESS can only provide peak-shaving services, as it only absorbs electrical energy to transform it for thermal energy injections.

D. Long-Term Storage

In islanded/isolated microgrids with large seasonal variations in generation and/or demand, ESS with the capacity to store and supply energy for a few months, can significantly reduce the operating cost of otherwise over-sized generation units. However, ESS technologies with such energy capacity are limited to PHS and HFCESS with large hydrogen tanks; PHS is limited to certain geographical areas with a large water reservoir close by, while transportation and maintenance costs could be an issue with large hydrogen tanks, especially in remote areas.

IV. CASE STUDIES

Aboriginal Affairs and Northern Development Canada (AANDC) reports that there are approximately 200,000 Canadians living in 280 Northern and Remote off-grid Communities (N&RCs) across the country. Currently, these communities dominantly rely on diesel-based generation, which presents various economic, social, and environmental challenges. From the economic perspective, diesel-dependency results in a high electricity price in the range of 0.45-2.50 \$/kWh depending on the communities' transportation access. A majority of N&RCs are only accessible through winter roads, whose availability is limited and depends on weather condition. These issues result in energy scarcity in some N&RCs; which subsequently affect their social and economic development. Furthermore, diesel-based generation contributes to environmental problems, such as Green House Gas (GHG) emissions and black soot, which also negatively impact the N&RCs.

In view of the aforementioned challenges, there has been a significant effort from government agencies, utilities, and universities to tackle microgrid-related problems in N&RC. As a result, several N&RCs are increasing or planning to increase the share of RES such as wind and PV in their microgrids. In this context, ESS are a key enabling element in the successful implementation of these projects. Examples of the role of ESS in N&RCs across Canada's provinces and territories is provided next; similar projects exist or are underway in various other remote communities across the world.

A. Kasabonika Lake First Nation (KLFN)

The KLFN community is a member of the Shibogama First Nations Tribal Council and the Nishnawbe Aski Nation - Treaty Number 9. The community is located 1,300 km northwest of Toronto and 500 km North of Thunder Bay, has a population of 914, and is accessible by winter roads that allow for a maximum weight of 80,000 pounds, although 40,000 pounds is a frequent and current restriction due to reduced ice thickness. The community is also accessible by air; however, a round trip from Thunder Bay costs \$1,500.

The KLFN energy demand is supplied by diesel fuel, which is transported via winter roads and stored in large tanks. Currently, the community's microgrid consists of a 1,500 kW, a 1,000 kW, and a 600 kW diesel engine. Data provided by Hydro One remote communities shows a peak demand of 850 kW and energy demand of 12 MWh per day, resulting in total fuel consumption of 1.0 million to 1.2 million litres per year, and an emission equivalent of 3,600 tons of CO₂ per year. Considering the relatively high diesel fuel price of \$1.8 per litre, the overall Operation and Maintenance (O&M) cost of the microgrid is \$3.7 million per year. Hence, the average cost of energy is 0.84 \$/kWh, which is significantly higher than energy price in southern Ontario (approximately 0.1 \$/kWh).

The electricity demand at KLFN has reached 90% of its supply capacity, and consequently, the community recently installed a 1,500 kW diesel generator replacing a 400 kW generator to overcome load restrictions that negatively impacted social and economic progress. In an attempt to evaluate the effectiveness of the RES deployment for the community, four wind turbines with a total capacity of 60 kW have been installed. A study considering 300 kW of wind power, with an estimated energy yield of 436 MWh/year, which is 10% of the community's annual energy demand, has been carried out. Furthermore, an extra 395 MWh/year has been estimated to be obtained from 300 kW PV panels, covering for 9% of the annual demand. Under these conditions, RES power penetration levels can be as large as 100% for a given hour, as shown in Figure 5. In these circumstances, BESS are needed to guarantee a stable and reliable performance of the microgrid, while considerably reducing fuel consumption and hence operating costs.

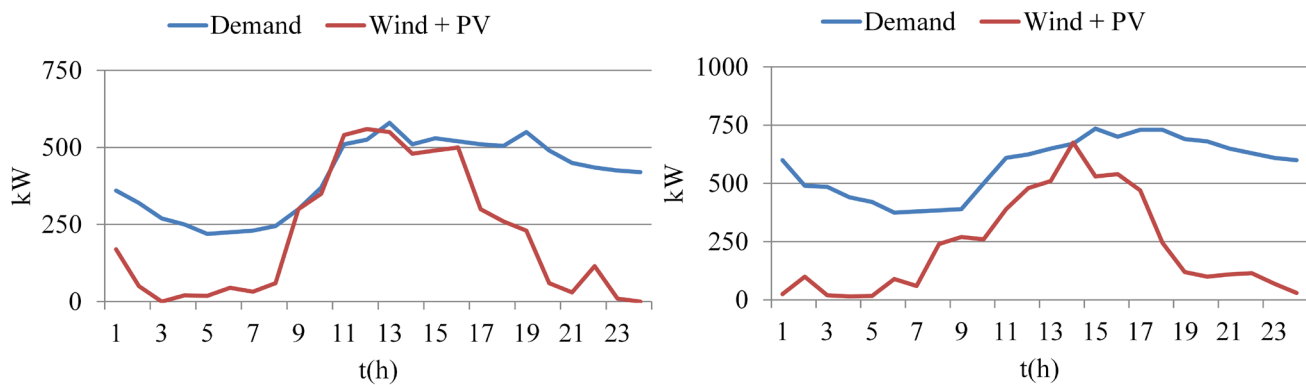


Fig. 5. RES and demand profiles at KLFN for 300 kW wind power and 300 kW solar power for (a) a typical summer day, and (b) a typical winter day

1. BESS

Simulations have demonstrated the effectiveness of BESS in mitigating the negative impact of RES fluctuations on the system performance. A model of the KLFN microgrid has been implemented and validated in PSCAD in collaboration between the University of Waterloo and Hatch Ltd. In the proof of concept results presented here, the battery is operated to compensate for wind generation fluctuations, while the 600 kW diesel generator is dispatched to supply a fixed load, thus leveling the total wind

turbine and BESS power output at 300 kW. Figures 6 and 7 demonstrate the performance of the system with and without the BESS, when the wind turbine output power changes/drops from 300 kW to 0 very quickly due to a wind gust exceeding the maximum acceptable turbine operating speed, thus tripping the wind generator. In this scenarios, BESS significantly improves the system frequency response, avoiding frequency stability problems.

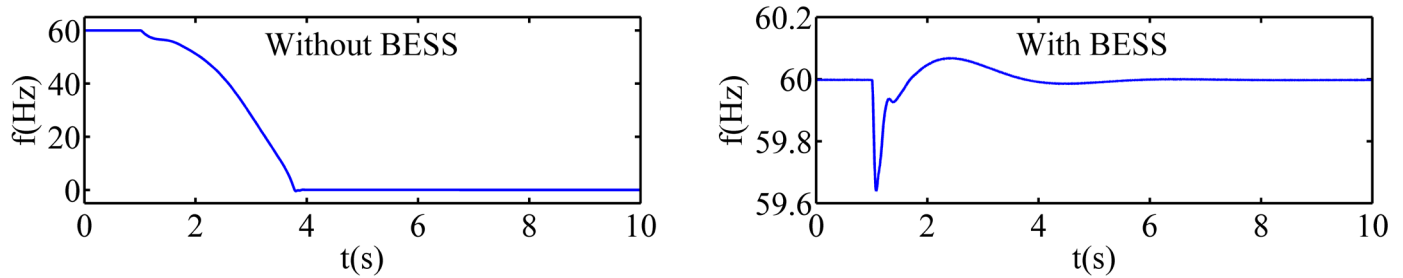


Fig. 6. Simulated frequency response of the system subject to outage of wind turbines at KLFN.

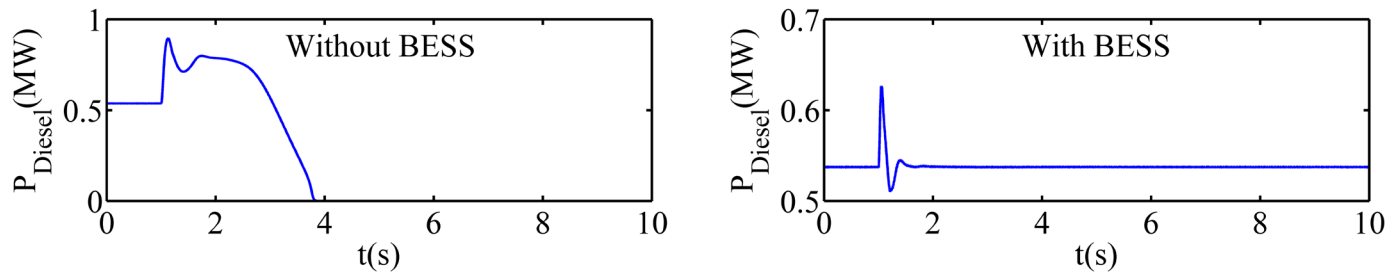


Fig. 7. Simulated diesel engine power output subjected to outage of wind turbines at KLFN.

In the aforementioned tests scenario, the BESS rated output power is 300 kW; however, deploying such a system may not be economically feasible for the community. Hence, battery sizing studies should be carried out to optimize the investment and O&M costs, and at the same time guarantee adequate system performance and maximizing fuel saving costs. Economic analyses show that installation of a 27 kWh BESS will reduce the O&M cost by \$330,000 dollars per year, as shown in Table 1. Note that, adding the BESS along with RES will reduce the fuel cost and emissions by 16%; however, there is a trade-off between the required capital investment to deploy RES and BESS, and the amount of cost, fuel, and emissions savings.

TABLE I

KASABONIKA MICROGRID ECONOMIC ANALYSIS

Description	Baseline	PV+Wind+BESS
		+Diesel
System characteristics		
RES penetration (%)	-	18%
BESS capacity (kWh)	-	27
Fuel and emission		
Fuel consumption (Million litres/year)	1.07	0.89

Emissions (MTon/year)	3.33	2.80
Cost		
RES Capital (\$ Million)	-	3.35
BESS Capital (\$ Million)	-	0.18
O&M Cost (\$ Million/year)	3.68	3.35

2. 2. TESS

Since KLFN community is located in Northern part of Ontario, Canada, it has significant thermal demand during winters from space heating, which is currently met mostly by wood pallets, heating oil and electricity. If the electricity is generated by RES, it can be used for space heating to reduce the use of fossil fuel. As mentioned previously, BESS require significant capital investments, whereas TESS are cheaper ESS options for the efficient integration of RES, while meeting the large thermal demand. In order to evaluate the impact of integrating TESS in the KLFN system, a study has been performed for the period from November 2014 to March 2015 using the actual measured electricity demand, generation from the installed PV units and wind turbines and by assuming that 30% of the electricity demand is to meet the space heating requirement during the Winter season; a 300 kW PV plant and 300 kW wind generation plant have also been considered in the case study.

A Unit Commitment (UC) model was coded in GAMS for a day with time resolution of half an hour for the 181 days, starting November 1st, 2014, to March 26th, 2015 and solved using CPLEX. The results obtained from the study are summarized in Table 2. Observe that by replacing electric heating with TESS, the operating cost of the KLFN microgrid can be reduced by up to 21% for the considered time window; also, significant reduction in fuel consumption and CO₂ emissions are observed, and around 645 kWh of RES generation curtailment can be avoided. From these results, one can conclude that the replacement of wood pallets and heating oil for space heating with TESS facilitates the integration of RES in the KLFN microgrid.

TABLE 2
KASABONIKA MICROGRID ANALYSIS WITH AND WITHOUT TESS

Item	PV+Wind+Diesel	PV+Wind+Diesel +TES
Operating costs (\$ Million)	1.39	1.094
Fuel consumption (Million l)	0.75	0.59
Emissions (Ton)	2,000	1,585
RES curtailment (kWh)	645	0

Note that with TESS, the 600 kW diesel unit is dispatched more frequently due to its lower fuel consumption, thus reducing operating costs. It is noted that the TESS charges when energy from the RES is available, and discharges to meet the thermal demand for space heating.

B. Bella Coola

Bella Coola Valley is a group of remote communities located 439 km north of Vancouver, BC, Canada, and has a population of 1,919. The communities are accessible by road, air, and marine ferry. These communities form the Bella Coola microgrid that has a main 25 kV distribution feeder, with two major load centers at Bella Coola and Hagensborg that have a peak demand of about 4.3 MW and 2.3 MW in winter and summer, respectively. The summer peak load is relatively stable, but the winter peak load depends on the weather conditions and ranges from 4 to 5 MW. There are 8 diesel generators installed at Ah Sin Heek generation station, with a total capacity of 7200 kVA. In addition, there are two run-of-the-river hydro generators, a 720 kVA and a 1400 kVA unit, located at the Clayton Falls hydro plant 7 km away from the Ah Sin Heek station. The total available generation capacity varies over the year, depending on the number of units available and the weather conditions.

During summer, which runs from April-May to late November, the demand is lower than the rest of the year, and at the same time the share of hydro generation is at its maximum due to adequate water supply; thus, the hydro units along with a few smaller diesel generators are sufficient to meet the peak load. Throughout this period, the larger hydro unit runs in isochronous mode, while other smaller gensets run in parallel to keep the frequency within tight ranges. During winter, the hydro power output can change considerably within hours, and thus diesel engines run in isochronous mode to regulate the frequency. In addition, the load is higher during winter compared to summer, and its variation over the 24-hour window is also higher because of varying consumption patterns during nights and days. As a result, all available diesel units are operated to maintain spinning reserve and adequate dynamic response capability, which results in the diesel generators operating at efficiencies below 35%.

Driven by the desire to decrease the system O&M costs, emissions, and dependency on diesel generators, the Hydrogen Assisted Renewable Power (HARP) project was developed for the Bella Coola microgrid. The project was aimed at implementing an HFCESS to store the surplus hydro generation and discharge it during on-peak hours, thus increasing the utilization factor of hydroelectric power. In addition, the HFCESS was aimed at shifting the energy production of diesel generators, thus increasing the efficiency of these units. The implemented HFCESS comprises an alkaline electrolyzer, a compressor, high-pressure hydrogen storage cylinders, and an air-cooled proton exchange membrane fuel cell; this technology has a high energy density, zero standby losses, and an efficient electrolysis process. The technical specifications of the HARP project are as follows:

- 1) The electrolyzer produces up to 5 kg/h hydrogen; maximum and minimum charging powers are 320 and 120 kW, respectively.
- 2) The compressor has a rated power of 50 hp and is able to pressurize the hydrogen up to 2850 psi.
- 3) The hydrogen storage tanks hold up to 100 kg pressurized hydrogen, equivalent to 3300 kWh of electrical energy.
- 4) The fuel cell has a rated power of 100 kW and a minimum run-time of 30 minutes.

An MGCC and monitoring system was developed, comprising a central optimization control, local controllers and PLCs, and other typical communication and automation equipment (see Figure 8). The microgrid control and monitoring system is aimed at finding the optimal charging/discharging schedule of the HFCESS to maximize the hydro generation utilization factor and minimize diesel fuel consumption. In addition, the system coordinates various assets of the microgrid to guarantee a stable and reliable operation.

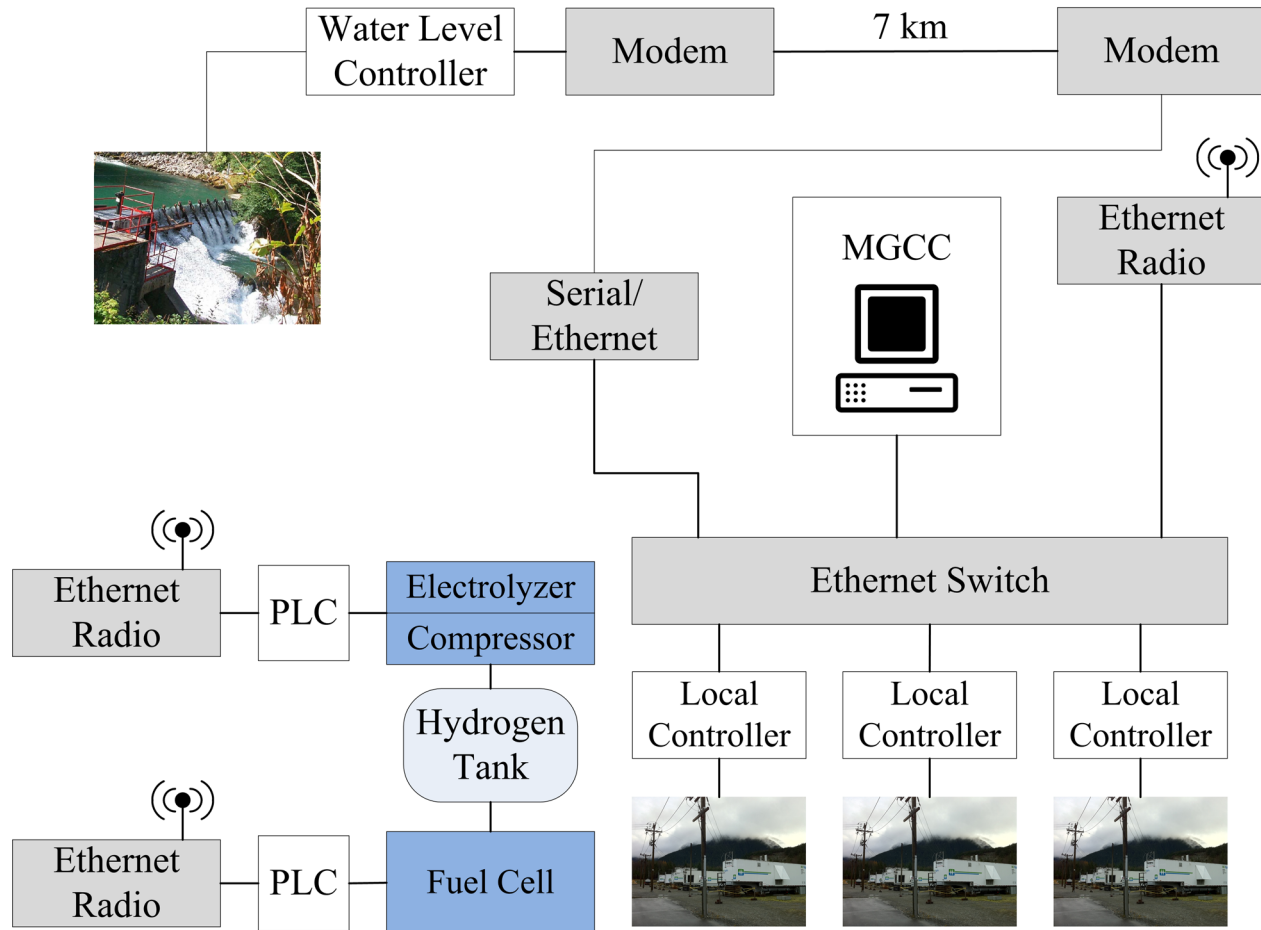


Fig. 8. Bella Coola microgrid control and communication scheme.

Various lessons have been learned from the HARP project. First, HFCESS was demonstrated to be a reliable and practical technology to displace diesel generator production, thus decreasing fuel costs and emissions. Second, the implementation of automatic control and communication technologies was proven to be a viable solution to address energy challenges in remote communities. Finally, careful analysis and tuning should be carried out to ensure a stable operation of remote microgrids, especially those that house various types of DERs.

C. Field, BC

Field is a remote community of approximately 159 electricity customers in the province of British Columbia, Canada, located

300 kilometers northwest of Calgary within the confines of Canada's Yoho National Park. The community is accessible by road via the Trans-Canada Highway. The community's electricity requirement is supplied by a 57-kilometer radial 25 kV distribution feeder from the Golden Substation. This feeder experiences frequent power outages of long duration, resulting in negative social and economic impacts on the community, because the area surrounding the feeder route experiences severe environmental conditions and is covered with natural forest. In addition, most of the feeder runs adjacent to the Canadian Pacific Rail line, restricting access to it for unscheduled repairs. Hence, the feeders experiences an average outage time of 8 h per outage; for example, on June 29th, 2013, the community experienced a 50 hour power outage until the technicians could access the location and repair. The load forecast for the Golden area predicted that the substation capacity would be exceeded by 1-2 MW at peak hours during the 2013-2014 winter.

To address the challenges pertaining to feeder outage and capacity constraints, two solutions were initially proposed: installing diesel generators, and installing a BESS. Although the former solution was cheaper than the latter, BC Hydro decided to install BESS since using diesel fuel to supply energy to the community is not an environmentally friendly approach, considering that Field is located within the Yoho National Park. The BESS was required to have peak shaving and islanding capabilities and required to withstand extremely harsh temperatures, as low as -50 °C. After evaluating the proposals, a sodium sulphur (NaS) battery was selected that met all technical and economic requirements; the BESS specifications are provided in Table 3. In addition, the PCS included a 1.25 MVA inverter and chopper accompanied by the necessary local and master controls. Due to remoteness and the terrain of the Field BESS site, satellite communication was not reliable and there was no cellular infrastructure. Hence, the communication between the BESS and the BC Hydro SCADA was established through a C-band satellite, while the short-haul communication between the islanding recloser and the BESS site was provided by a 900 MHz Speed Net radio (see Figure 9).

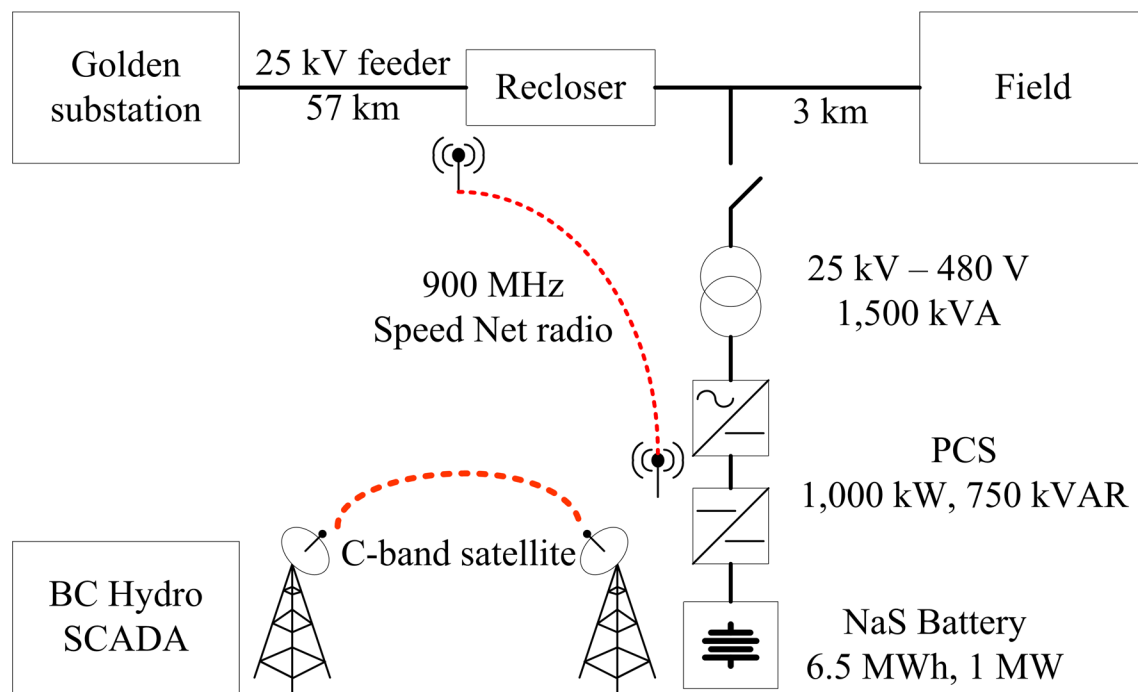


Fig. 9. Field BESS configurations and telecommunications.

TABLE 3

FIELD BESS PROJECT BATTERY SPECIFICATIONS

Power	1 MW	Capacity	6.5 MWh
Expected service life	15 years	Efficiency	85%
Rated dc voltage	640 V	Fast charging time	9-10 hours
Power density	99 kW/m ³	Energy density	59.6 kWh/m ³

The BESS has been operational since July 2013, and has been actively used in both peak shaving and grid-forming applications. The BESS injects power in parallel to the main feeder every day from 4 to 8 PM, to supply a part of the community's electricity demand, thus performing peak-shaving. Afterwards, the BESS charges at 750 kW for an hour, or until the battery State of Charge (SOC) is 100%. Since July 2013, there have been 22 outages, during which the BESS has provided 120 h of back-up power to the town of Field. As a result, more than 15,000 customer hours lost (CHL) has been avoided by the BESS; Figure 10 shows the CHL before and after the BESS installation. Among these outages, the longest one was of 24 hours duration, resulting in complete discharge of the BESS. The occasions when the BESS could not provide back-up power were either due to loss of C-band satellite communication, or a fault between the BESS and the town of Field.

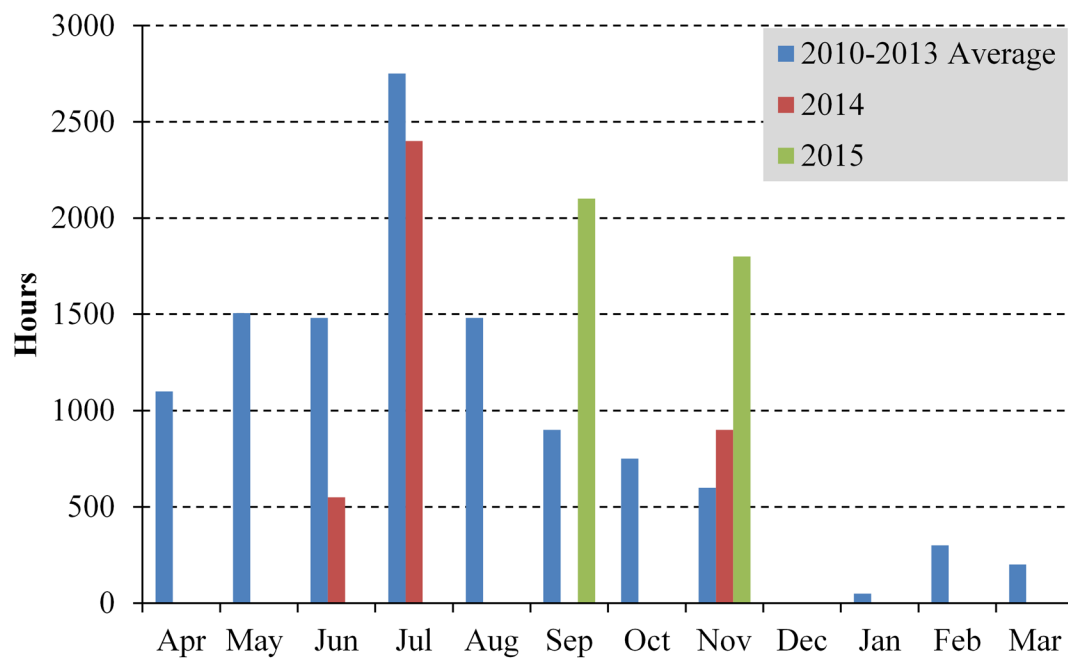


Fig. 10. CHL in Field before and after BESS installation.

Acknowledgments

The authors would like to thank Dr. Mariano Arriaga, Dr. Amir Hajimiragha, Dr. Steven Wong, a BC Hydro team, and Mr. Greg Gaudet for sharing some of the data and information presented in this article.

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