BATTERY PERFORMANCE UNDER EXTREME COLD CONDITIONS AND THE POTENTIAL OF ELECTRIFIED FLEETS AS STATIONARY STORAGE

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Abstract

The pursuit of NetZero targets has become a top priority for many countries around the world, and significant efforts are underway to decarbonize the transportation sector and energy generation. This study presents an overview of stationary storage technologies and assesses their feasibility as storage in extreme environments. A series of experimental results are shown to assess the performance of certain Li-ion chemistries under cold conditions as well as to discuss the impact of long-term cold storage on battery performance. The study further explores the potential for Electric Vehicles (EVs) and Vehicle to Grid (V2G) technologies to be used as stationary storage options. The analysis demonstrates that V2G technology can effectively harness the potential of EVs to store and supply energy to the grid and can provide a reliable and cost-effective solution for stationary storage.

Introduction

The British Antarctic Survey (BAS) has committed to achieving a net-zero carbon operation for its research stations in the Antarctic by 2040. In order to meet this target, a comprehensive upgrade of the current energy generation system is necessary, particularly for the generators fueled by marine gas oil (MGO). The transition towards cleaner energy sources will require a reliable and sustainable source of energy, as well as an effective energy storage system that can accommodate the power demands of the research stations. One such research station is located on Bird Island, which is situated on the Northwest tip of South Georgia in the Southern Atlantic Ocean. This island is renowned for its abundant wildlife, including 50,000 breeding pairs of penguins and 65,000 breeding pairs of fur seals, and is considered one of the most ecologically rich sites in the world [1]. The station operates all year round and has a maximum capacity of twelve individuals.

Currently, Bird Island utilizes three primary fuel tanks that contain MGO to power the generators and boilers. Diesel generators are commonly used to supply energy to research stations located in the harsh and remote environments of the Antarctic. However, the use of diesel generators is associated with greenhouse gas emissions and environmental pollution, which can have significant long-term impacts on the fragile Antarctic ecosystem. In 2019, the generator in Bird Island used 28,315 Liters of MGO with the average electricity usage presented in Figure 1. This translates to CO_2, CH_4 and N_2O Greenhouse Gas (GHG) equivalent emissions of 85,155 $kgCO_2e$ to supply the electrical load demand of 111.65 kWh/day.

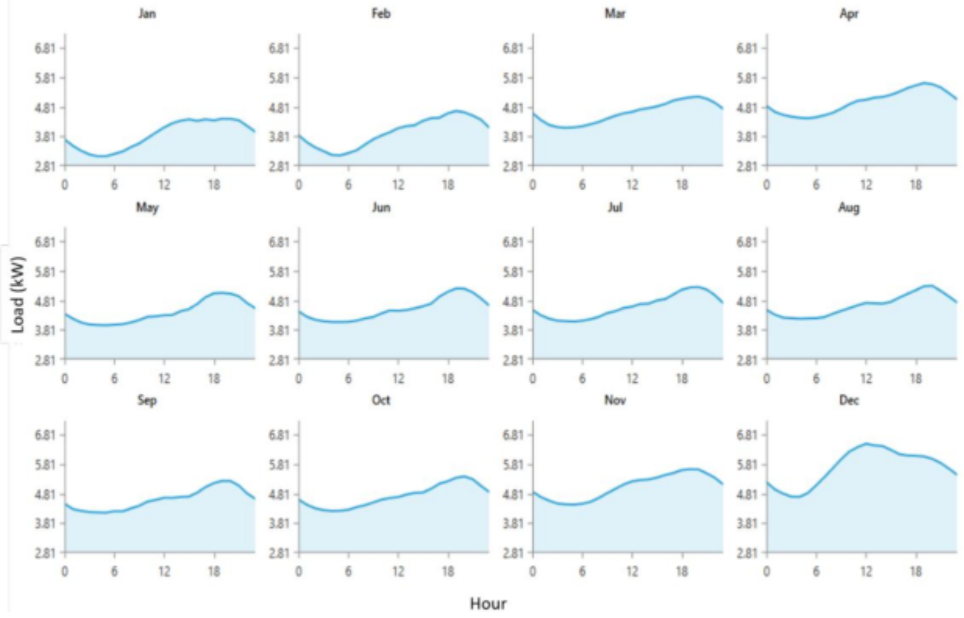

Figure 1. Bird Island daily load profile for each month of 2019.

There are unique challenges associated with Bird Island's station because wind turbines cannot be used for electricity generation due to the need to protect the bird populations, and solar availability is limited in certain months of the year and hence unable to meet the full stations load. Energy storage using battery systems will have to be installed to meet the load demand for the "extended nights."

A variety of battery chemistries can be considered for the stationary storage energy needs of the station. Table 1 provides a brief overview of four battery types with their generic strengths and weaknesses.

Table 1. Advantages and Drawbacks of Different Technologies

	Lead-Acid	Redox-Flow	Nickel-Cadmium	Sodium Sulfur
+	- Low cost [2], [3] - Longevity [3], [4]	- Scalable [5] - Long lifetimes [6]–[8] - High energy efficiency [7] - Cost-effective [7]	- High cycle life [9], [10] - Performance at cold temperatures [10]	- High energy density [11], [12] - Relatively long life cycle [13] - Reasonable efficiency [13]
-	- Heavy - Sensitive to temperature [2] - Require regular maintenance - Low specific energy [3] - reduced capacity at cold temperatures [10]	- Lower energy density than lithium-ion batteries [7] - low stability [7]	- Memory effect (reduced capacity if not fully recharged) [9], [10] - Toxic [10], [14] - Low energy density [10] - High rate of self-discharge [10]	- High cost [13] - Need to be heated initially [12] - Low power density [15] -Thermal losses can be crippling in cold temperatures

Implementing these four technologies at a large scale in the Antarctic station poses several challenges. Firstly, the station has stringent restrictions on the materials that can be transported and utilized. Secondly, the transportation of equipment to Antarctica is highly costly. Consequently, high energy density and low weight solutions are crucial for successful large-scale deployment. Finally, the harsh cold weather conditions can have significant effect on the performance of the chemistries.

An assessment of the irradiance profile and load demands of the station revealed that a total of 6 MWh of battery storage would be necessary to completely substitute fossil fuels for the station's energy needs. It is noteworthy that even for a modest load, the battery investment and capacity requirement would be considerable.

A potential way to reduce the amount of stationary storage capacity would be to use standby electric vehicles and their batteries to temporarily increase the capacity of the storage system. Vehicle-to-Grid (V2G) is a technology that allows electric vehicles to be used as a distributed energy resource and is based on bidirectional charging technology [17] The basic principle of V2G is to use the battery of an electric vehicle as a source of energy storage to support the Load [16] This means that electric vehicles can be used as a source of stationary storage during periods where vehicles are not used.

V2G and Li-Ion Batteries

The three most common chemistries used in current electric vehicles are lithium nickel manganese cobalt oxide (NMC), lithium iron phosphate (LFP) and lithium nickel cobalt aluminum oxide (NCA) hence they will be the ones considered as a V2G storage. Table 2 highlights the benefits and drawbacks of these technologies.

Table 2. Advantages and Drawbacks of different Li-Ion Batteries

	Lithium Nickel Manganese Cobalt Oxide (NMC)	Lithium Iron Phosphate (LFP)	Lithium Nickel Cobalt Aluminum Oxide (NCA)
+	- High energy density [17]–[19] - Long lifespan [19], [20] - thermal stability [17]–[19] - Good power capability - High capacity [17], [19], [21]	- Higher degree of safety [17], [21] - Long lifespan [21] - Wide operating temperature range [22] - Good capacity [17], [21] - Low cost [21] - Low self-discharge [21]	- High energy density [21] - Long lifespan [17], [21] - Good power density [21]
-	- Susceptible o thermal runaway [20] - Capacity fade [19] - Safety issues [21]	- Lower energy density compared to NMC [17] - Lower open circuit voltage [17]	- Can overheat [17], [23] - High costs [21] - Safety issues [21]

The impact of low temperature conditions on performance is a major concern for both Antarctic stations, as well as colder climates and extreme environmental events. In order to estimate the change of performance and assess the viability of the chemistries used in vehicles under extreme conditions, a series of experiments were performed.

In a climatic chamber, the batteries were stored at different temperatures (25°C, -15°C and -30°C) until their temperature aligned with that of the environmental chamber. Subsequently, the batteries were discharged at a rate of C/3 for NMC and NCA and C/2 (for LFP) until a cut off voltage of 3.2V for NCA and NMC and 2.6V for LFP was reached.

Figure 2 shows the performance of the various chemistries under different conditions and results are summarised in Table 3.

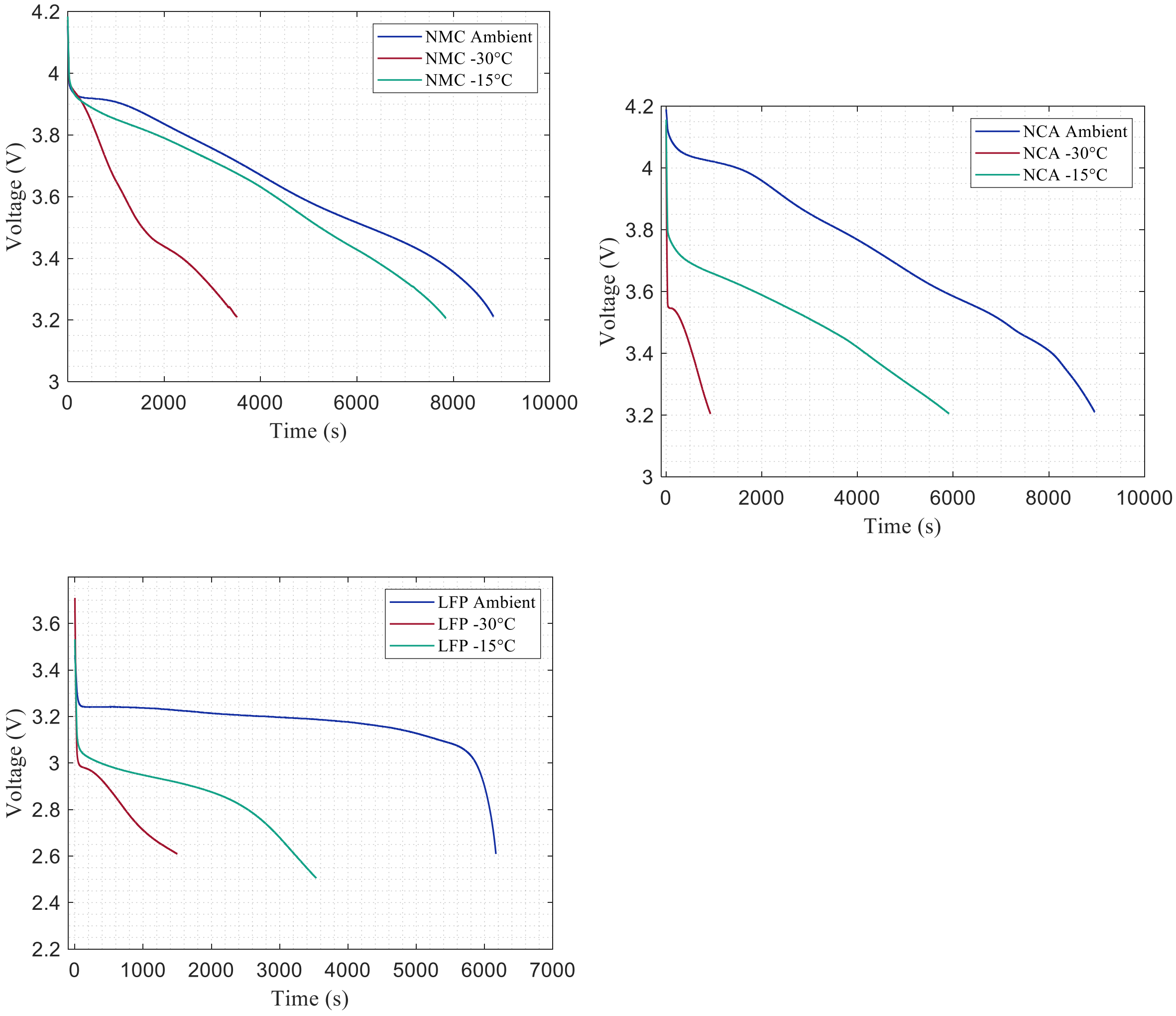

Figure 2. Discharge profile under different conditions for NMC, NCA and LFP

Table 3. Absolute and Relative Capacity of Li-Ion Batteries at different Temperatures					
Chemistry	Ambient	-15°C		-30°C	
NMC	3000 mAh	2176 mAh	72.53 %	971 mAh	32.4%
NCA	2900 mAh	1648 mAh	56.82%	254 mAh	8.7%
LFP	1800 mAh	983 mAh	54.6%	241 mAh	13.4%

Overall, the results of the experiment indicate that NMC performed the best, with only a slight increase in internal resistance at -15°C. In contrast, NCA exhibited a higher increase in internal resistance and the most significant reduction in performance. Although the initial increase in internal resistance of LFP between -15°C and -30°C was relatively small, it was only able to discharge 13.4% of its capacity at -30°C.

To evaluate the potential of stationary power available through vehicle-to-grid (V2G) electrification, a transferable conversion methodology is proposed.

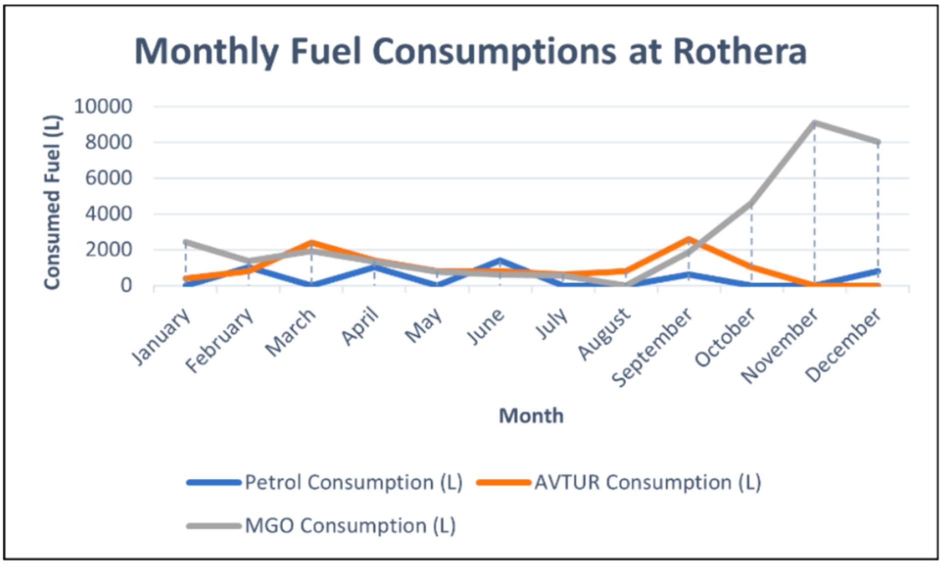

Figure 3. Monthly Fuel Consumptions, 2018

The monthly fuel consumption data for both petrol and AVTUR (jet fuel) for the vehicles in the Antarctic station of Rothera is provided, and it can be seen from Figure 3 that the annual consumption of petrol and AVTUR is 4,800 and 11,600 litres, respectively. The UK Government fuel conversion factors are applied to estimate the calorific value of the fuels, considering net calorific values that take into account the latent heat of water produced by combustion engines. As the exhaust gases of Antarctic vehicles contain water vapour, net calorific values are used in the calculations [24]. Accordingly, the conversion factors for petrol and AVTUR are calculated as 8.97 kWh/L and 9.75 kWh/L, respectively [24]. Multiplying the fuel consumption data with the conversion factors provides the energy consumption for petrol and AVTUR.

The useful work output of the internal combustion engines that are used in vehicles at Rothera is determined, taking into account engine efficiency values. It is important to note that combustion engines' efficiency is temperature-dependent and generally reduces at lower temperatures. Based on the British Antarctic Survey (BAS) data, a vehicle efficiency value of 39% is assumed to apply to all vehicles irrespective of fuel type and drivetrain variations. Thus, calculating 39% of each fuel's energy consumption yields the energy that results in useful work. However, electric vehicles require accounting for the efficiency values of both electric motors and batteries, which are significantly greater than those of combustion engines. As the efficiency values of electric vehicles in Antarctic conditions are currently inconclusive, the U.S. Department of Energy [25] reports that electric vehicles have an efficiency of approximately 77% in moderate-temperature operating conditions. Dividing the useful output values by 77% yields the electrical load demands for each respective fuel. From the energy and fuel conversion roughly 80MWh of energy will be needed in a year to supply the equivalent of conventional fuel. Significant investments in clean generation will be needed in order to charge all these battery vehicles with the cold temperatures leading to further load needs to allow for adequate heating of the cells to allow charging. A project is currently ongoing to assess the most effective solution between charging efficiency and ambient temperature but will not be covered in this paper.

Currently there are 74 vehicles at Rothera station ranging from skidoos to gators, cranes tractors and loaders. Having the energy requirements for the vehicles and knowing the number of operational hours, the average battery size of the battery fleet can be estimated as 80kWh. During winter the active Rothera station personnel are reduced by 80% and leading to lower vehicle utilizations. If 50 out of the 74 vehicles are unused during the winter this will lead to roughly 4MWh of stationary battery available through V2G.

These vehicles could be transported to the Bird Island station which would reduce the stationary battery needs by 60% to power the load. However, considering the length of the trip and the dimension and weight of the vehicles this would only be carbon positive if the ship carrying them is carbon neutral. Hence transportation of the vehicles needs to be practical and taken into consideration.

Long term cold storage

To assess the performance of cells following extended storage at various states of charge (SOC), a second experiment was conducted. Two cells each of NMC and NCA batteries were stored at -15°C for ten months, with one cell fully charged and the other at 50% SOC. After allowing the cells to rest and reach ambient temperature, their open circuit voltage was measured, followed by charging at 1C. The cells were then rested for two days in an ambient temperature of 25°C and where discharge was at C/3 rate.

Table 4. Battery Performance after 10 months at -15°C

Chemistry	Open circuit Starting Voltage (V)	Open circuit End Voltage (V)	Charge (mAh)	Discharged Capacity
NMC(100%)	3.46	4.09	2000	85%
NCA (100%)	3.63	4.16	1409	90%
NMC (50%)	3.54	4.15	1761	86%
NCA (50%)	3.58	4.14	1423	88%

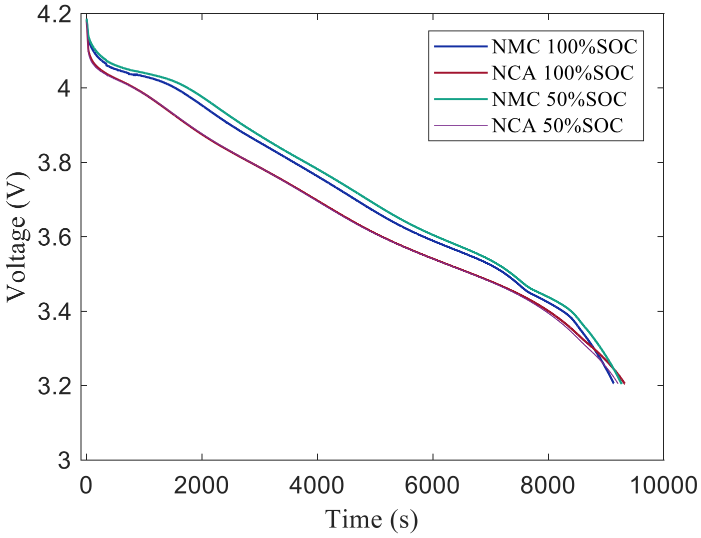

Figure 4. Discharge performance after 10month at -15°C

From the results on table 4 and figure 4 there is no major performance difference between cells stored at 50% and 100% for both chemistries. Both chemistries appear to have lost 10% of the availability capacity in the 8-month period under cold storage. Additional experiments will be needed to see the long-term storage performance in even colder temperatures.

EV Fleet as storage in other sectors

The extreme case studies previously presented illustrate the significant investment and methods necessary for replacing fossil fuels and has already shown the potential of utilizing standby EV and V2G technology for powering the load as stationary storage, leading to the question, in which other sectors can V2G also be employed? A rough estimate of potential storage from various electrified fleet and specialised equipment in the United Kingdom is presented in table 5.

Table 5: Fleet Electrification capabilities

Vehicle Type	Capacity (kWh)	UK Fleet Size (#)	Operating Time	Total daily available capacity
Electric Bus (Volvo 7900 Electric)	Up to 470 [26]	37,800 [27]	5am-12-am	13.23 GWh
Ambulance (VCS E-DCA)	Up to 108 [28]	387 front line ambulances. 178 rapid response vehicles. 175 non-emergency ambulances [29]	Day and night	0.13 GWh
Waste Collection Vehicles	300 [30]	17,900 [31]	2-5 days a week	5.37 GWh
Delivery Van (Royal Mail)	50-75 (Peugeot)	41,500 vans and 6,200 trucks and trailers. [32]	During daytime	2.98 GWh
Tractors	130 (John Deer electric tractor)	11,490 [33]	During daytime	1.5 GWh

As can be seen the utilization of electric vehicles presents considerable potential for energy storage. Electric buses, with their large fleet size and high capacity, are highly suitable for V2G applications, despite their limited operation to daytime hours. Postal delivery vehicles offer a similarly large fleet size, with 47,700 vehicles operated by Royal Mail in the UK, although their capacity is lower than that of electric buses but have more opportunities to be utilized as storage by providing promising opportunity for storing energy during evening and night hours. In contrast, ambulances, despite their large overall fleet capacity, are not as well-suited for V2G applications due to their round-the-clock operation that limits access to their storage capacity. Waste Collection Vehicles exhibit the most potential for V2G applications, with two key advantages: a high storage capacity of up to 300 kWh and significantly shorter operating times than other applications, making them an ideal candidate for energy storage.

Conclusion and considerations

The phase-out of fossil fuels will heavily rely on stationary batteries, with potential contributions from idle fleets of electric vehicles for the provision of additional energy. It is important to consider the performance of different battery chemistries under various environmental conditions. In this study, it has been shown that cold temperatures have a significant impact on battery storage systems on both capacity as well as accelerated degradation of performance. The difference in state of charge for NMC and NCA cells under long term cold storage had little impact on the cells' performance however additional tests in even colder temperatures with a wider range of SOC will be of interest. Further work needs to be done in order to identify an optimised storage temperature for cells considering both the performance of the cells as well as the energy requirement to sustain that performance. Additional testing will also need to be performed to study charging efficiencies under different conditions.

The integration of V2G hybrid systems presents various challenges, including regulatory and standardization issues that require appropriate categorization of such systems. Additionally, the utilization of electric vehicles as storage results in additional battery degradation due to the increased cycle count, reducing their overall lifecycle [34]. Finally, the adoption of such a technology en masse would require asset management considerations assessing the criticality of different systems for potential viability as well as developing new health indexes, together with the developments of suitable control technology.

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