energies

MDPI

Article

Electrochemical Cells and Storage Technologies to Increase Renewable Energy Share in Cold Climate Conditions—A Critical Assessment

Yao Ahoutou *, Adrian Ilinca and Mohamad Issa

Wind Energy Research Laboratory, Université du Québec à Rimouski, 300, Allée des Ursulines, Rimouski, QC G5L 3A1, Canada; adrian_ilinca@uqar.ca (A.I.); missa@imq.qc.ca (M.I.)
* Correspondence: yao.ahoutou@uqar.ca; Tel.: +1-418-732-4683

Abstract: The energy efficiency of a renewable energy system is inextricably linked to the energy storage technologies used in conjunction with it. The most extensively utilized energy storage technology for all purposes is electrochemical storage batteries, which have grown more popular over time because of their extended life, high working voltage, and low self-discharge rate. However, these batteries cannot withstand the very low temperatures encountered in cold regions, even with these very promising technical characteristics. The cold northern temperatures affect the batteries' electromotive force and thus decrease their storage capacity. In addition, they affect the conductivity of the electrolyte and the kinetics of electrochemical reactions, thus influencing the capacity and speed of electrons in the electrolyte. In this article, which is intended as a literature review, we first describe the technical characteristics of charge–discharge rate of different electrochemical storage techniques and their variations with temperature. Then, new approaches used to adapt these electrochemical storage techniques to cold climates are presented. We also conduct a comparative study between the different electrochemical storage techniques regarding their performance in the harsh climatic conditions of the Canadian North.

Keywords: renewable energy; energy storage systems; batteries; cold northern temperatures; storage capacity; kinetics; adaptation method; containerized solutions for batteries

check for updates

Citation: Ahoutou, Y.; Ilinca, A.; Issa, M. Electrochemical Cells and Storage Technologies to Increase Renewable Energy Share in Cold Climate Conditions—A Critical Assessment. *Energies* **2022**, *15*, 1579. https://doi.org/10.3390/en15041579

Academic Editor: Abasifreke Ebong

Received: 19 January 2022
Accepted: 18 February 2022
Published: 21 February 2022

1. Introduction

World energy consumption is still highly dependent on non-renewable energies, with a rate of about 90% in 2017, as shown in Figure 1 [1]. Oil remains the most used, with an estimated annual consumption of 4 Gt.

Quebec's situation is much better, as 44% of Quebec's energy balance comes from renewable energies [2]—this is one of the world's highest proportions, well above the global average of 10% [1]. The electricity production from entirely renewable sources can explain this performance (i.e., 200 TWh from hydroelectricity and wind power). Electricity and biofuels meet 35% and 9% of Quebec's energy needs, respectively (see Figure 2).

Despite this fact, the northern communities of Quebec and Canada face a cold climate and remain heavily dependent on fossil fuels for their energy needs.

However, the combustion of fossil fuels generates high costs, financial vulnerability to external elements, and greenhouse gas emissions. Moreover, fossil fuels are the origin of the world's accelerating climate crisis. Therefore, it is imperative to develop green energy techniques around the globe, especially in the Canadian North. However, there are technical, economic, and social barriers worldwide to renewable energy development. In addition to these barriers, there are harsh weather conditions in the isolated regions of Northern Canada.

In remote areas that cannot connect to electricity grids, electricity generation is more expensive due to the necessary power generation and the high cost of transporting diesel fuel.

Indeed, electricity in northern regions is exclusively produced by diesel generators [3–6]. The cost of electricity produced under these conditions can be several times higher (up to 9 times) than the Canadian norm. For example, in Kugaaruk, Nunavut, the residential electricity rate, which is not subsidized, is over nine times higher ($1.14/kWh) than the Canadian average ($0.12/kWh) [7]. The cost of producing electricity by diesel generators operated by Hydro-Quebec, the provincial energy producer, is approximately $0.75/kWh in Kuujjuaq.

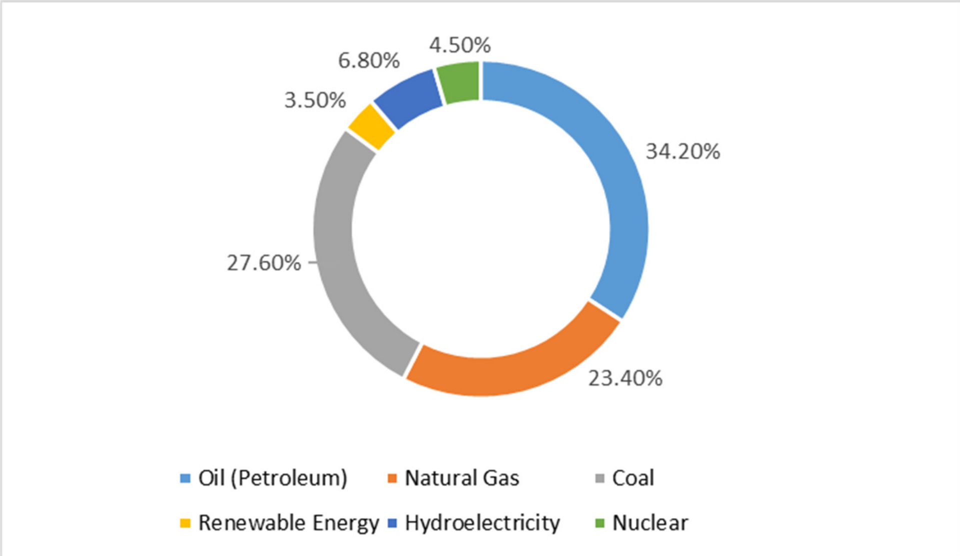

Figure 1. World energy consumption in 2017 (adapted from [1]).

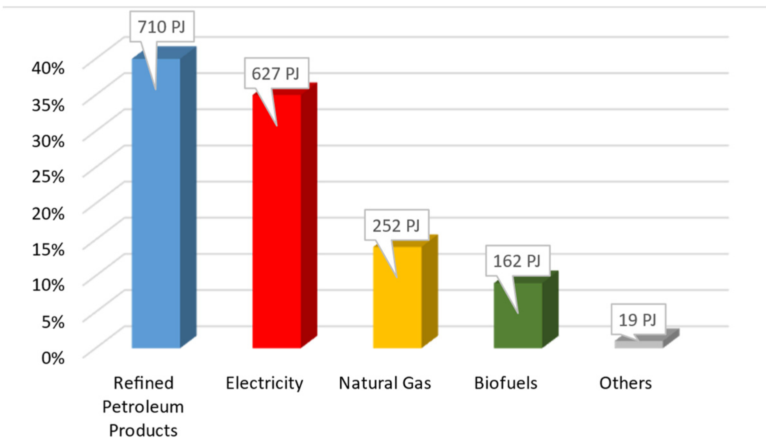

Figure 2. End-use demand by fuel in Quebec (2017) (adapted from [2]. "PJ" means "petajoule").

In comparison, the cost of producing hydroelectricity in the rest of Quebec is $0.03/kWh on-grid and $0.40/kWh off-grid [5,8]. This dependence on fossil fuels does not spare mining companies. Mining operations need to consume a large amount energy to ensure stable and continuous operation. Conventional energy sources mostly meet this high energy requirement. The cost of energy represents between 30 and 35% of the total cost of mining operations [9–11]. Therefore, reducing energy costs is a primary objective for any mining operator.

In addition, public pressure to improve environmental, social, and governance (ESG) standards and the perpetual need to reduce energy costs have motivated northern communities in general and mining companies, in particular, to move towards renewable energy.

These factors encourage the search for alternatives to fossil fuels, such as wind energy, solar energy, biomass, hydroelectric energy, marine energy, and geothermal energy.

Small green power plants can be installed to provide electricity to supplement diesel power plants. These plants are generally referred to as hybrid systems. The primary functions of green power plants are to help reduce diesel fuel consumption, ensure energy independence, and contribute to environmental protection.

However, wind and sun, the primary sources of electrical energy produced by small green power plants, are random and intermittent. They are subject to regional, seasonal and daily variations, resulting in an inconstancy of electrical power supply, high production unpredictability, uncertain forecasts, and an imbalance between production and consumption. Hybridization with other power generation sources and the combination of small green power plants with energy storage systems are thus necessary to overcome this problem. Chen et al. [12] argued that integrating energy storage is the most viable and promising approach to mitigate the consequences of wind and solar intermittency.

The efficiency of green energy plants is thus effected by the efficiency of energy storage that could make them more competitive than traditional fossil energy technologies [13,14]. Indeed, energy storage in northern areas, subject to cold climates, remains problematic. In this context, the lithium battery (Li-ion) presents very promising technical characteristics but does not resist the very low temperatures encountered in the northern regions of Canada (sometimes down to −50 °C). Therefore, it would be necessary to adapt this technology to these operating conditions, particularly reheating.

This review covers the impacts of extreme weather conditions on renewable energy installations and penetration levels of renewable energy in northern regions and mines. It also covers energy efficiency in northern communities, different means of energy storage, and electrochemical batteries' efficiency in extremely cold operating conditions.

2. Potential for Renewable Energy Use in Northern Communities

The overall objective of this study is to contribute to the increase in the penetration rate of renewable energies in northern communities with cold climates. Therefore, it is essential to discuss the potential for renewable energy in these communities. Indeed, diesel power plants and stoves provide electricity, space heating, and hot water production in all northern villages. Energy costs are high because of the need to import petroleum products over long distances. In addition, the small and widely dispersed population, high equipment operation and maintenance costs due to a lack of skilled labor, and necessary parts and tools also influence prices.

In addition, each house in these northern villages has a diesel furnace that provides hot water. The price of Arctic diesel was approximately $1.93/l in 2015 in Nunavik [5,8]. Figure 3 [15] depicts the significant price disparity between the northern territories and other Canadian provinces. In addition to these high economic costs, the environmental impact amounts to thousands of tons of CO_2 emitted each year, contributing to air pollution and global warming in an Arctic environment already subject to permafrost degradation, thus impacting both ecosystems and society [16].

Furthermore, as with all of Canada, petroleum is the form of energy that covers almost all transportation energy needs in the northern areas. The Yukon example [17] in Figures 4 and 5 shows that for end-use energy demand by fuel type in the Yukon in 2017, refined petroleum products accounted for 6.1 PJ (77%) of demand, followed by electricity at 1.6 PJ (20%) and natural gas at 0.2 (3%). Biofuels and other fuels, such as coal, coke, and coke oven gas, were absent (0 PJ). In the same year, energy demand for end-use totaled 7.9 PJ. Transportation accounted for 58% of total demand, followed by the industrial sector (20%), the commercial sector (13%), and the residential sector (9%).

However, developing new methods to provide electricity, space heating, and hot water is crucial. Several research studies have concluded the need to use green energy in northern communities isolated from the electrical grid.

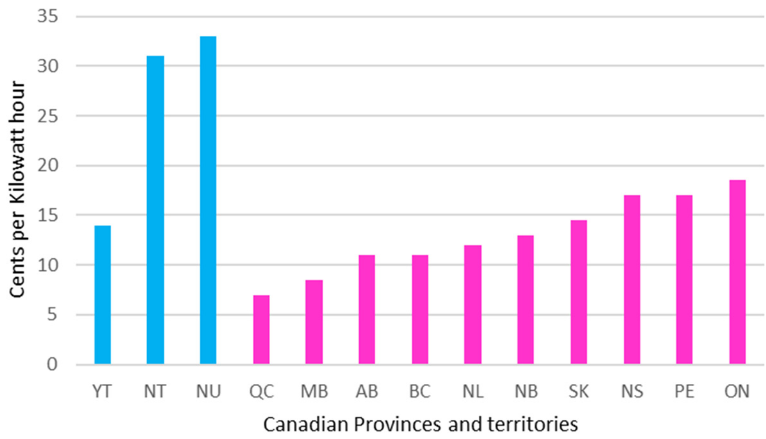

Figure 3. Representative electricity prices in Canadian provinces and territories in 2016 (adapted from [15]).

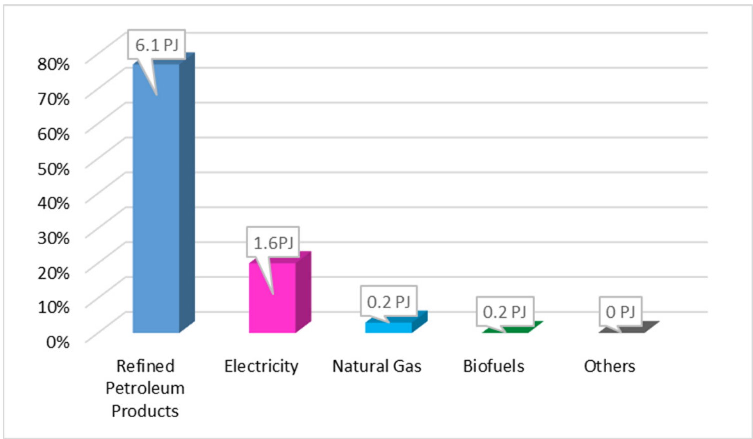

Figure 4. End-use energy demand by fuel in the Yukon in 2017 (adapted from [17]).

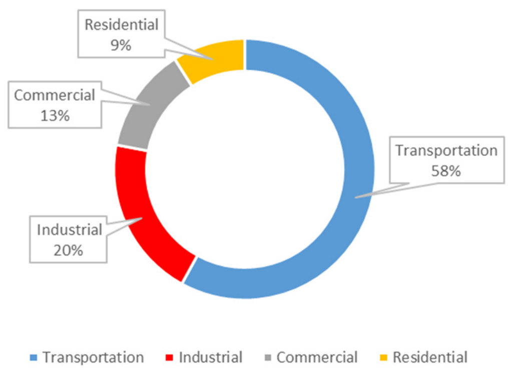

Figure 5. End-use energy demand by sectors in the Yukon in 2017 (adapted from [17]).

For example, Longo et al. [7], using HOMER software, conducted a study that addressed the accessibility of green energy and alternatives to reduce the dependence on petroleum derivatives for electricity generation in underserved communities and remote northern populations. The adverse effects of climate change strongly influence these locations. The study site was "Red Lake Canada" in Ontario, part of Canada's remote northern areas. The conclusions drawn from this study emphasize the need for a combination of renewable energy sources to achieve good results; wind power and solar photovoltaic energy in this case.

Thompson and Duggirala [18] also conducted a renewable energy feasibility study in an off-grid community in Canada. Their research looked at biomass, wind, and solar energy for a small off-grid research station that relied on diesel for electricity and propane for heat. Although the electrical load was 115 kW, a demand-side management energy audit identified 15–20% potential savings. Reducing the electrical demand to 100 kW saved $27,000 in biomass, $49,500 in wind, and $136,500 in solar construction expenditures. The RETScreen software analyzed the economic and environmental benefits of producing 100 kW of power from these three renewable energy sources to alternative-diesel equipment ($160/kW). Biomass-combined heat and power was the most competitive in any price range from $0.80 to $2.00 per liter of fuel.

Majorowicz and Grasby [4] investigated the possibilities for geothermal energy development to meet local energy demand in northern Canadian settlements. They found enough geothermal energy in the Mackenzie and Yukon Corridor areas to heat northern settlements at a competitive cost.

3. Energy Efficiency in Northern Communities

Northern Canadian communities are heavily dependent on fossil fuels. Renewable energies are an interesting option to diversify the energy supply of these communities. However, which technology is the best adapted and most interesting for these communities? Are there other measures that could help these communities reduce their dependence on petroleum products? These are questions that have been addressed in previous research.

For example, Belzile et al. [8] carried out a literature study with the primary goal of identifying prospective energy efficiency and renewable energy solutions for the northern energy setting. Several energy sources and technologies for heating buildings and industrial processes were presented in this study to evaluate their implementation potential to reduce fossil energy consumption in Northern Quebec. This literature review concluded that the isolation and size of northern communities did not make it economically feasible to connect to national grids. Therefore, electricity was produced from diesel generators, with about 33% efficiency. Space heating was conducted by burning diesel, accounting for about 50% of the communities' energy needs.

The mining industries in the area are also heavily dependent on fossil fuels. Alternative solutions have been explored with current policies to reduce greenhouse gas emissions. In Alaska, trials on the economics of air source heat pumps have had dismal results. When combined with a horizontal geothermal system, water-source heat pumps have demonstrated promising results. Solar energy is becoming more and more competitive as the price of photovoltaic panels continues to decrease. Solar collectors can be used to heat water. However, storage is required because the sun is not present in high latitudes for much of the year. Wind turbines need a heating system to de-ice the blades to make them competitive. With an alternative energy source such as wind, electrical storage is also required. Batteries can be used, but the capacity of most batteries decreases in cold temperatures.

Serra [6] recommended facilitating and encouraging the development of alternatives to fossil fuels in the northern regions of Canada. She analyzed different cases of renewable energy implementation in Canada and other northern areas of the world, notably in Alaska and the Yukon, to highlight the main barriers to developing these new technologies. These recommendations are summarized in Table 1.

However, she concluded that wind energy technologies are, by far, the most suitable solution for Arctic conditions. Despite all the barriers to green projects, renewable energy has an exciting future in northern Canada, and renewable energy will become more competitive in the marketplace as the price of petroleum products increases.

Table 1. Example of actions for an energy plan (adapted from [6]).

Steps	Actions
1	Increase the efficiency of existing generators. Implement newer machines, use cleaner petroleum products, and integrate better control systems.
2	Use the heat produced by the generators as waste heat.
3	Use low-consumption equipment to reduce the number of products consumed.
4	Consider creating heat and power by other means (e.g., wind, solar, and hydro).

4. Impact of Extreme Weather Conditions on Renewable Energy Installations

The massive development of renewable energy technologies is one of the essential medium-term objectives to achieve the energy transition. These technologies transform a renewable energy source into heat, cold, electricity, or mechanical energy, and an energy source is considered renewable if its use does not affect its future availability. Therefore, renewable energy is defined as energy that can be renewed quickly enough to be considered as such on a human lifetime scale. However, the extreme climatic conditions in Canada's far north have hindered the development of these renewable energies, essentially wind energy, solar energy, biomass, hydroelectric energy, marine energy, and geothermal energy.

The presence of extreme weather during the winter seasons affects renewable energy installations [6]. In addition, the formation of frost during very long winters impacts the operation of facilities.

These effects are summarized below:

- The high air density and wind speed of big cold regions are particularly helpful to wind energy operations. On the other hand, wind turbine blades are generally subject to icing throughout the winter. Blade icing can significantly reduce power output or completely stop the wind turbines [6,19–21]. Unfortunately, this phenomenon can also lead to blade failure.
- Icing also affects wind measurement equipment and transmission lines by increasing the loads on the structures, creating a situation conducive to failure [19–21].
- In cold climates, snow and ice can accumulate on photovoltaic modules, blocking sunlight, reducing power production, and (in rare cases) damaging the modules.
- In the case of storage systems using batteries, they suffer a significant loss of capacity in cold weather.
- In the case of hydroelectric dams, the infrastructure must deal with ice and snow that can cause damage or limit the operation of the structures. In addition, river levels are low in winter when demand is at its highest.
- The presence of permafrost and its behavior during periods of global warming are other aspects to consider. Climate change is affecting the soils of Canada's far north. Permafrost plays an important role in surface and subsurface hydrology, affecting the water regime. This accelerated melting also affects the foundations of various structures, including those of wind turbines [6].
- Regarding biomass, organic matter is scarce. It is therefore not the best energy alternative in the Canadian North.

5. Different Means of Storage

The primary idea behind energy storage is to move energy available during low-demand periods to high-demand periods while utilizing a fraction of the fuel that a conventional production machine would use.

Energy storage, along with other energy difficulties such as energy resource development, energy conversion, and energy conservation, is one of the most globally critical energy strategies [14]. Energy storage helps close the gap between supply and demand [22]. It also increases the performance and dependability of energy systems and plays an important part in energy conservation. Energy storage is also necessary for renewable energy sources such as the sun, wind, and tides. Indeed, the latter have seasonal or daily variations and are not always available.

Energy storage techniques can be categorized into the following categories based on their technological types:

- Mechanical (flywheel).
- Thermal (sensitive or latent refractory).
- Potential (gravity hydraulics and pumping turbine).
- Pneumatic (compressed air in a cavern or bottles).
- Electrical (superconducting inductance and super-capacitors).
- Chemical (electrochemical batteries, redox batteries with electrolytic circulation, hydrogen, and fuel cells).
- The selection of a storage mode depends on several criteria, including [23]:
- The capital cost of the storage and power electronics.
- Cycling and calendar life.
- Energy efficiency (storage size, thermal management, and structure).
- Safety and the environment.
- Temperature, humidity and/or salinity constraints.

The concept of storing surplus energy is not new, and numerous researchers have tried to improve and innovate storage technologies. These storage techniques have been compared in the scientific literature, and the most suitable have been identified for different applications.

Hossain et al. [24] covered all the basic concepts of energy storage systems, including their evolution, elaborate classification, and comparison. They reported a huge rise in power and energy units in 2018 compared to 2017 (Figure 6), as well as forecast of global energy capacity (Figure 7). Their study covered a wide range of energy storage techniques.

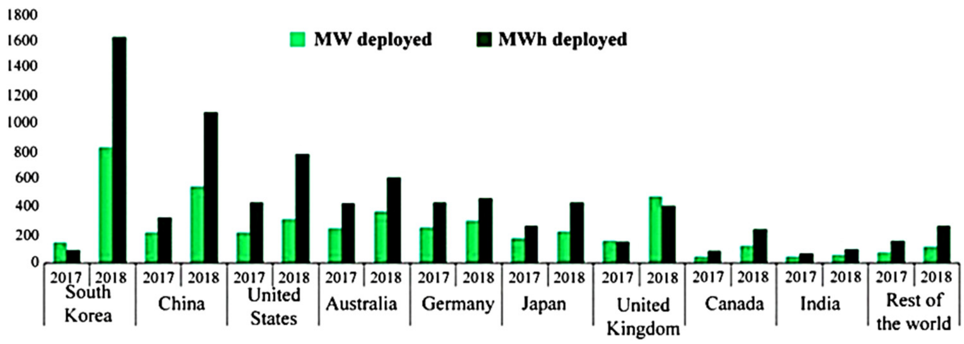

Figure 6. Capacity of global energy storage in 2017 and 2018 [24].

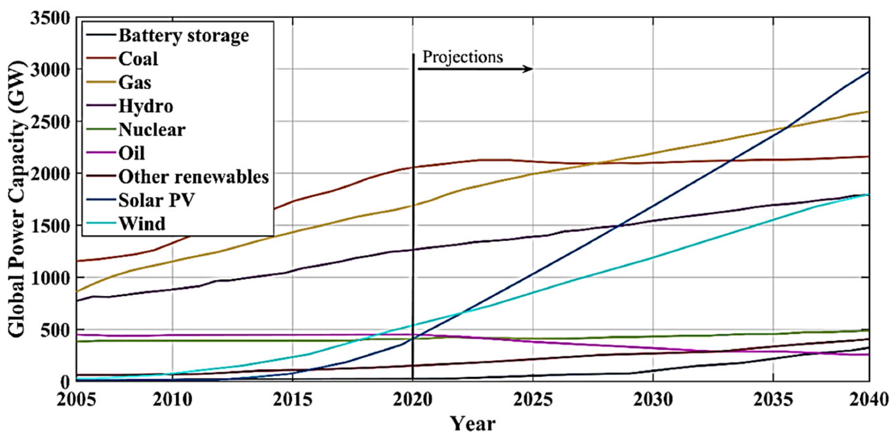

Figure 7. Forecasts of global energy capacity for various sorts of energy sources [24].

Dimitriev et al. [14] addressed the essential concepts of solar energy storage for long-term usage, and they concluded that electrochemical and redox-flow batteries had the best energy storage efficiency. This energy efficiency goes up to 90% for lithium-ion batteries [14] and 86% for redox-flow batteries [25]. Ibrahim et al. [26] described several storage systems, some of which are already in use and others which are still in the development stage. They saw storage as the weakest link in the energy chain but a crucial element for renewable energy development. Storage is a technical solution for grid management, ensuring real-time load leveling and a way to better use renewable resources by avoiding load shedding in periods of underproduction.

6. Electrochemical Storage Techniques

Of all the existing energy storage techniques, the most widely used for all applications is electrochemical storage with batteries. The considerable advantage of mobility can partly explain batteries' success over other solutions [27]. However, mobility is not the only advantage. Their cyclability, i.e., their capacity to store and discharge energy reversibly over several hundred cycles, is also essential. This cyclability, accompanied by very high energy efficiency (up to 97% for lithium-ion batteries), makes batteries extremely attractive in stationary applications, such as the storage of electricity from primary renewable energy sources to balance supply and demand in isolated power grids [27].

Electrochemical storage technology includes all rechargeable batteries and flow batteries, which store electrical energy in the form of chemical energy. It is one of the most and best established technologies available [22,24,28].

Batteries (or accumulators) are therefore electrochemical systems that store energy in chemical form and release it in electrical form. These batteries have variable energy densities, which are low for lead batteries at 20–30 Wh/Kg and much higher for lithium technologies at between 150 and 2000 Wh/kg [22]. Figure 8 shows the distribution of different electrochemical batteries based on their energy density and power [22,29].

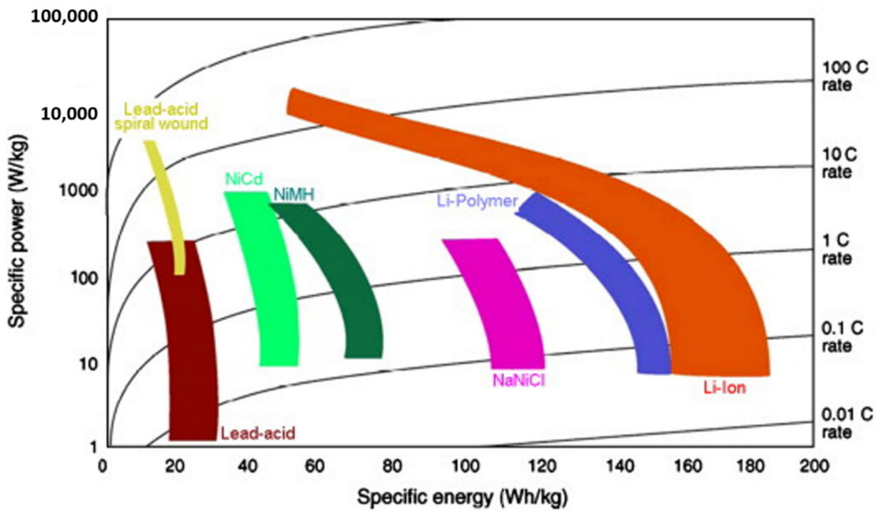

Figure 8. Distribution of different electrochemical batteries based on their energy densities and power [22,29].

A battery's operation is based on a reversible electrochemical system. The current is produced by the circulation of electrons between two plates or electrodes:

- A positive electrode capable of yielding or capturing electrons.
- A negative electrode capable of giving up or taking in electrons.

The current is generated by electrons moving from the positive electrode to the negative electrode via a metal wire in order to power a resistor. Ions formed as a result of this electron transfer travel from the cathode to the anode via the electrolyte. This causes the battery to discharge.

Therefore, a battery is characterized first by two oxidizing–reducing couples (e.g., lead/lead oxide, carbon/lithium cobalt oxide, and carbon/lithium iron phosphate) that exchange electrons. The fundamental entity of a battery is then formed by the combination of two plates (or two insertion materials for the li-ion battery) [30].

The two electrodes are submerged in an electrolyte solution (or electrolyte), which can be liquid or gel in consistency. The reaction between the solution and the electrodes causes the movement of electrons and ions in the solution [31,32]. Thus, the electrolyte has the functions of ensuring ionic conduction and, more generally, participating in the chemical reaction. A porous insulator (or separator or ion-exchange membrane) separates the two electrodes while allowing for the passage of ions.

Connecting a device to the battery causes electrons to move because of the potential difference. Electrons go from the anode to the cathode through the external circuit. For example, in a lithium-ion battery (see Figure 9), the positively charged lithium ions, attracted by the negative charges of the electrons, leave the anode and return to the cathode [33]. The charging process causes electrons to return in the reverse direction, from the cathode to the anode (Figure 10). For this purpose, an external charger is connected to the battery. As a result, lithium ions move from the cathode to the anode to balance the electrical charge. When all the ions have passed, the battery is fully charged. Lithium ions move back and forth in the electrolyte throughout the battery's life between the anode and the cathode.

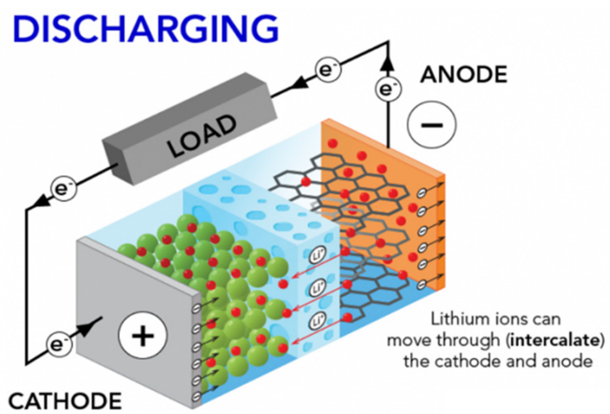

Figure 9. In-use lithium-ion battery operation [33].

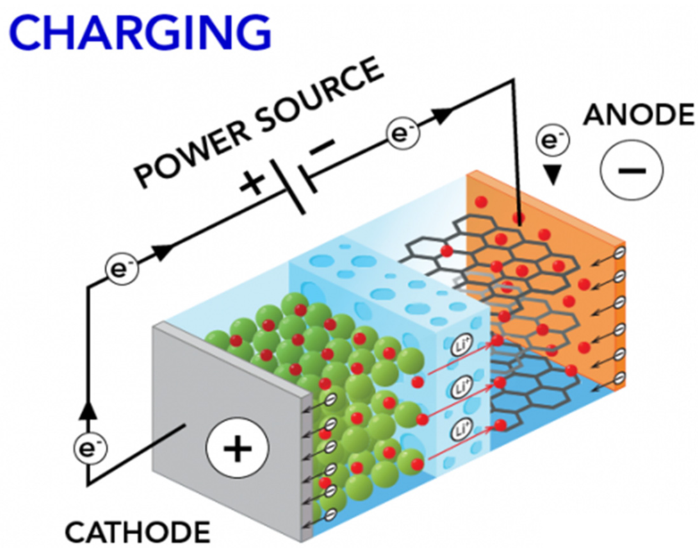

Figure 10. Operation of a lithium-ion battery under load [33].

The characteristic quantities of rechargeable energy storage batteries and flow batteries are [23]:

- The voltage across an open circuit (the equilibrium voltage of the battery at rest).
- Storage capacity (characterizes the maximum quantity of electrical charges available to discharge it completely).
- State of health (ratio between its total capacity at time t and its total capacity in new condition).
- Internal resistance (depends on charge status, charge/discharge regime, temperature, and health condition).
- Coulombic efficiency (ratio between the capacity that the battery can give back fully charged and the capacity that must be given back to recharge it entirely).
- Charge/discharge state (the percentage of available capacity).
- Charge/discharge rate (a standardization convention based on battery capacity): a 20 A current must be applied for 0.5 h to a battery with a nominal capacity of 10 Ah.

Despite a standard operating principle, different battery technologies depend on the materials used. Notable examples include lead batteries, lithium-ion batteries, lithium metal batteries, lithium polymer batteries, sodium beta batteries, air metal batteries, nickel-based batteries such as nickel–cadmium (Ni–Cd) and nickel–metal hydride (Ni–MH) technologies, flow batteries, and electrochemical capacitors. Among these technologies, only some of the more developed ones are the subject of this study. These include lead–acid batteries, which paved the way for accumulators as early as 1859 and are still present in each of our thermal vehicles. They are also used to store the energy of photovoltaic and wind power systems. Nickel–cadmium batteries appeared on the market in the mid-1960s, and nickel–metal hydride batteries were introduced in 1990. Lithium-ion and lithium polymer batteries are becoming more common [34,35].

6.1. Lead Batteries

The history of rechargeable batteries begins in 1859, when physicist Gaston Planté developed the lead–acid battery (with a unit voltage of 2 volts) at the Conservatoire National des Arts et Métiers in Paris [23,27]. This accumulator is made up of two lead electrodes submerged in a sulfuric acid electrolyte in an aqueous solution and charged with Daniel batteries. The anode is constructed of lead dioxide, whereas the cathode is made of sponge lead. The lead–acid battery incorporates additional elements such as wood, cardboard, cables and connectors, paper, steel, and polyethylene in addition to the active materials such as the anode, cathode, and electrolyte [24]. This battery has rapidly evolved since the end of the 19th century for multiple applications (such as lighting and the storage of energy produced by a dynamo), including electric vehicles [23,27]. Lead–acid batteries have been used for over 150 years and are a very reliable, mature, and universally recognized technology [24,36]. They have a modest energy density of roughly 30 Wh/kg (due to lead's large molar mass, which exchanges 2 moles of electrons for 217 g per mole), but their inexpensive cost makes them one of the most extensively used batteries today [27]. Lead is the metal that can be recycled the most efficiently. As a result, lead–acid batteries are the only electrochemical energy storage technology that can be nearly entirely recycled. More than 99.4% of lead–acid batteries are recycled in Europe and the United States [24,36].

Figure 11 depicts the overall chemical reactions and major components of a lead–acid cell.

The lead from the negative electrode dissolves in the electrolyte when discharged and then produces lead sulfate by releasing two electrons that pass to the positive anode via the external circuit. The positive electrode's lead also dissolves in the electrolyte in the form of lead sulfate. If the discharge is complete, the electrolyte is only composed of distilled water, losing much of its dissolved sulfuric acid.

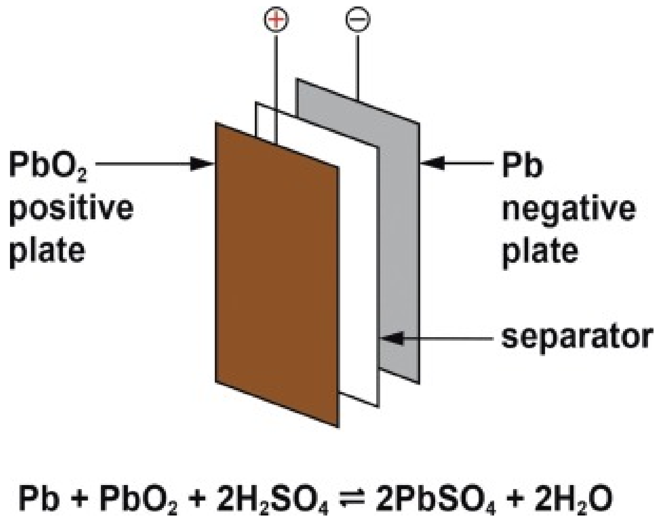

Figure 11. A lead–acid battery's chemistry and major components [36].

When recharging, the two polarities disulfate and the electrolyte is regenerated. SO_4^{2-} ions are put into solution. The positive electrode is peroxidized with the formation of lead dioxide (PbO_2), and ions are released, thus increasing the concentration of H+ ions in the electrolyte.

Different types of lead–acid batteries were addressed in [24], including flooded lead–acid batteries, sealed lead–acid batteries, AGM (absorbed glass mat) batteries, and gel batteries.

The characteristic elements of the lead–acid battery are [37]:

Charging capacity: The total quantity of electricity a battery can provide after being fully charged is its capacity. It is expressed in ampere/hour (Ah).

Energy density: At an average voltage of 2 V, the theoretical energy density is 168 Wh/Kg. In practice, the best lead/acid batteries do not exceed 45 to 50 Wh/Kg. This is due to the use of electro-chemically inert materials (enclosure, grid, etc.) and the partial use of active materials (from 35 to 55%).

Efficiency: Lead–acid batteries have an energy efficiency of 70–75%. During the electrochemical operations of charging, discharging, and self-discharging, 25% of the electrical energy are wasted, primarily as heat.

Depth of discharge and life span: The depth is the ratio between the already discharged capacity and the battery's nominal capacity. It is expressed as a proportion of its total capacity. A depth of discharge of 80% indicates a deep discharge. A battery should not undergo deep discharges because its life span rapidly decreases with the average depth of discharge. When a battery is deeply discharged, harmful phenomena such as sulfation, freezing, and electrolyte stratification more quickly occur than when the depth of discharge is shallower. During discharge, the voltage U across the battery is $U = E - RI$ where E is the open circuit electromotive force (i.e., 2.10 V), R is the battery's internal resistance, and I is the discharge current. During discharge, the internal resistance increases because the electrolyte concentration decrease in the electrodes' pores. The higher the I, the faster the voltage U falls. The faster the drain, the lesser the battery's capacity.

As a result, the discharge current must not be very high. Moreover, a battery slowly discharges even if it is not used: this is self-discharge. The self-discharge rate is mostly determined by the alloy chosen for the grids: the discharge rate is particularly high for Pb–Sb alloys (lead–antimony), where it reaches 5% per month for new batteries at 25 °C. The rate of self-discharge significantly rises with temperature and time: it can reach 1% per day for a Pb–Sb battery at the end of its life.

Charging a lead–acid battery: The charging speed of a battery is fast at the beginning of the charge and then slows down. When the state of charge exceeds 80 to 90%, a voltage and/or current regulation limits the charging speed. Indeed, any extra energy given to the battery would be wasted in the forms of the heat and electrolysis of the water contained in the electrolyte. A battery should not be recharged too quickly with too high a current or voltage. Generally, the charging current should not exceed 1/10 of the discharge current in 10 h (C10). When the battery reaches its maximum state of charge during charging, hydrogen and oxygen bubbles are detected at the negative and positive electrodes, respectively. These gases are produced due to the electrolysis of the water in the electrolyte. This is the degassing phenomenon, which depends on several parameters, including the maximum voltage at the battery terminals allowed by the regulation (charge controllers must cut or limit the current to avoid excessive degassing), the temperature (the higher the temperature, the more degassing occurs at low voltages), and the discharge speed (degassing begins at lower states of charge when the charge speed increases). An equalization charge is necessary to fully charge each accumulator to avoid imbalances between the different accumulators that make up the batteries. This equalization consists of charging the batteries with a low current but at a voltage higher than the voltage generally applied at the end of the charge [37].

6.1.1. Technical Characteristics of the Charge–Discharge Rate of Lead Batteries and Their Variation According to the Temperature

Lead–acid batteries are very fragile. They are sensitive to overloads, partial charges, deep discharges, rapid charging, and temperatures above 20 °C. Therefore, the operating temperature of a battery is an essential factor that determines its life span. It should be noted that the life of lead–acid batteries is generally between 2 and 5 years in typical applications [38]. The optimum operating temperature for batteries is 20 °C. The life of a battery decreases by 50% for every 10 °C above 20 °C. Thus, at 30 °C, the life span is reduced by 50%. At 40 °C, it is reduced by an additional 50%; this would mean a life of a quarter of what it would be at 20 °C [38]. Rapid discharge, rapid recharging, and a warm environment are the main reasons for increasing battery temperature. High battery temperature leads to the accelerated aging of the battery. The chemical reaction accelerates with increasing temperature. The increase in temperature also increases the rate of self-discharge [39].

In addition, temperature plays a vital role in properly recharging a battery. This is because the voltage of the battery varies according to its temperature. Cold batteries have low voltages, and hot batteries have high voltages. Thus, a cold battery will not be sufficiently charged at fixed recharging voltages, leading to probable sulfation. In contrast, a hot battery will be overcharged. This can lead to overheating with the possibility of thermal runaway and risk of explosion. It is therefore essential to reduce the charging voltage when the temperature rises. Temperature compensation is necessary when the temperature exceeds 30 °C or is below 10 °C for an extended period [38]. Increasing the temperature enhances a battery's capacity as well.

On the other hand, the capacity of a battery diminishes with cold. This decrease in capacity is equal to 1% per degree Celsius below 20 °C. The lower the battery's charge, the lower the acid density and the less the battery is protected against freezing. Thus, for batteries with liquid electrolyte, with the risk of their destruction by freezing, it is essential at negative temperatures that they be well-charged and that an equalization charge is carried out regularly to destratify the liquid electrolyte and avoid an over-density of sulfuric acid in the lower strata and pure water in the upper strata [38,39].

6.1.2. Solutions for Adapting Lead–Acid Batteries to Cold Climates

Lead–acid batteries can fail in various ways, depending on the design, use mode, and environment. Manufacturers usually provide information on how long their battery designs will last in a specific application. However, several characteristics that can reduce battery life apply to most designs and applications. The ambient temperature is one of the most critical factors in forecasting battery life. Battery voltage and current are reduced at low ambient temperatures, whereas battery life is reduced at hot temperatures. For example, in the winter, automobile batteries frequently fail to start the engine for two reasons. The first is that the power required to start a cold engine increases (voltage times current). Second, the battery's power is lowered because cold temperatures impair the battery's ability to supply both voltage and current. Conversely, high summer temperatures reduce battery life because of increased grid corrosion and other side reactions that lead to battery failure.

Battery life is further reduced when batteries are used in uncontrolled situations, such as outdoor telecommunications cabinets, photovoltaic systems, and marine applications. To prevent a battery from overheating in hot settings, manufacturers frequently propose lowering the charging current or float voltage. For an extended period, storage on an open circuit might also shorten battery life. Over a battery's "shelf life," chemical reactions will gradually discharge it. Because heat speeds up these chemical reactions, storing a battery at a somewhat cold temperature extends its shelf life. At low temperatures, the rates of most battery breakdown mechanisms slow down. The electrolyte in a fully charged battery does not freeze until it hits minus 40 °C. However, when a battery is drained, the freezing temperature rises to minus 10–15 °C.

Variations in specific gravity as a charge state function affect the electrolyte's freezing temperature (Table 2) [40]. The specific gravity of the electrolyte is defined as the ratio of the sulfuric acid solution's specific gravity to that of distilled water. In cold climates, a battery can freeze if discharged, and the expansion of volume due to freezing will destroy the battery.

Table 2. Electrolyte freezing temperature of lead–acid batteries as a function of specific gravity (adapted from [40]).

Specific Density	Freezing Temperatures (°C)
1.0	0
1.5	−3.3
1.	−7.8
1.5	−15
1.	−27
1.5	−52
1.0	−71

In cold climates, the density of the electrolyte in lead–acid batteries is increased to avoid the risk of freezing, whereas it is decreased in tropical climates. Table 3 shows the advantages and downsides of these acts [40].

Table 3. The benefits and drawbacks of raising the specific gravity of lead–acid battery electrolytes (adapted from [40]).

Climate	Cold Climates	Temperate Climates	Tropical Climates
Specific Density	**1.29–1.30**	**1.25–1.28**	**1.20–1.23**
Positive effect	• Reduction in the risk of freezing • Increased electrochemical activity • Increased capacity at low temperature	X	• Less corrosive electrolyte • Increased service life
Negative effect	• More corrosive electrolyte • Decreased service life (destruction of grids and separators)	X	• Decrease in capacity • Decrease in performance for fast discharges

Wang et al. [41] propose the addition of carbon materials to the cathode to improve the performance of lead-acid batteries operating at very low temperatures. By evaluating the High-Rate Partial-State-of-Charge cycle and dynamic charging with various carbon contents, they concluded that the percentage of carbon between 0.3% and 0.9% provides a good improvement in the performance of lead-acid batteries in cold climates.

Giess [42], on the other hand, evaluated the performance of VRLA–AGM stationary lead–acid batteries under extremely cold conditions. The batteries retained up to 56% of their capacity and could be recharged at −30 °C operation. A valve-regulated lead–acid battery (VRLA) has a one-way discharge valve. AGM stands for "absorbed glass mat" (electrolyte absorbed in glass fiber). The electrolyte in this type of battery is completely absorbed into a highly absorbent material made of glass fibers, resulting in a device that is spill- and acid-leak-proof. In addition, the glass fibers offer lower electrical resistance, promoting current flow between the plates for more efficient electrical transfer [24,43,44]. The good performance of VRLA/AGM stationary batteries at extremely cold temperatures supports the expansion of their application range, and Häring and Giess [45] affirmed that application-oriented studies have corroborated the amazing performance of these batteries at temperatures as low as −30 °C.

6.2. Nickel-Based Batteries

Like any electrochemical battery, nickel batteries are rechargeable. They are used in various electronic devices, electric and hybrid vehicles, aerospace, energy storage, and many other applications. They are very robust and tolerate abuse, including overcharging and deep discharges [46]. They appeared just after lead–acid batteries over a hundred years ago. They use nickel oxyhydroxide (NiOOH) as the positive electrode [24,47,48] and operate over a wide temperature range, with a flat discharge curve.

These batteries consist of a negative electrode, a positive electrode, and a separator, as shown in Figure 12 [49].

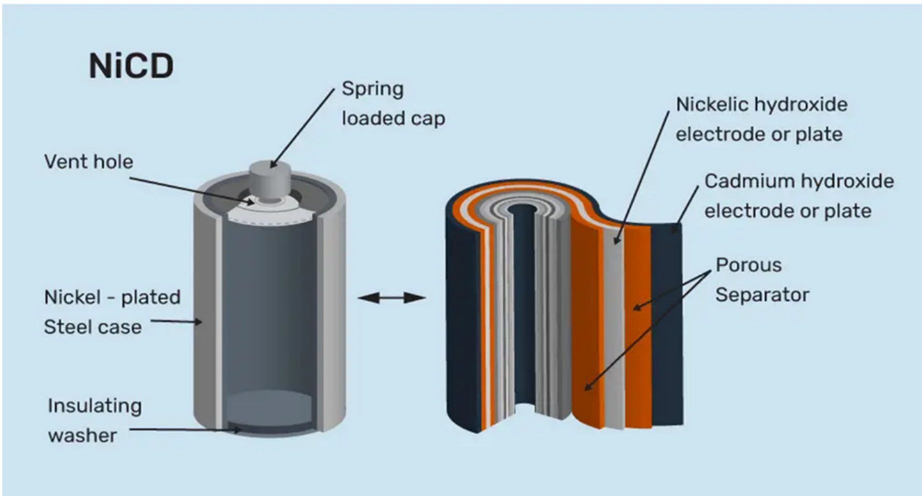

Figure 12. The nickel–cadmium battery's fundamental structure [49].

There are several variants of nickel-based batteries: nickel–hydrogen (Ni–H_2), nickel–iron (Ni–Fe), nickel–zinc (Ni–Zn), nickel–cadmium (Ni–Cd) and nickel–metal hydride (Ni–MH) [24,47]. Only the latter two are popular in various applications, including emergency and vehicle propulsion applications [24,47].

6.2.1. Technical Characteristics of Charge–Discharge Rate of Nickel–Cadmium (NiCd) Batteries and Their Variation with Temperature

Nickel–cadmium batteries appeared in the middle of the 20th century and promoted the dazzling success of nickel batteries [12,48,50]. They were small enough to power portable devices such as radios. With versions ranging from the small to large, nickel–cadmium batteries emerged as the first popularized rechargeable batteries. These very robust and stable batteries have been used in various fields, including aviation. However, they have a handicap in the toxicity of cadmium [51,52]. As a result, nickel–cadmium heaps contain dangerous compounds whose distribution and disposal in developed countries are rigorously restricted. Aside from their toxicity, nickel–cadmium batteries have a low specific energy (around 80 Wh/kg) and a high self-discharge rate (10% per month) when compared to other electrochemical batteries. The memory effect has been reported but is a misconception that surrounds this technology [24,48,50].

However, these batteries have many advantages, including a high number of cycling rate (up to 2000), vibration resistance, long life expectancy, and the ability to operate at −40 °C [48,50].

6.2.2. Technical Characteristics of Charge–Discharge Rate of Nickel–Metal Hydride (NiMH) Batteries and Their Variation with Temperature

Nickel technology matured in the early 1980s with the introduction of nickel metal hydride batteries. These batteries have a higher self-discharge rate (20% in the first 24 h and 10% per month thereafter), a longer life span, and higher specific energy. The NIMH battery gets its name from its main components: nickel (noted Ni) and metal hydride (MH). The first element serves as a positive electrode. The second is the compound that allows for hydrogen storage. It is a mixture of potassium hydroxide and hydride alloy. The latter is made from lanthanum (rare earth) and nickel [53].

A nickel metal hydride battery cell has a voltage of about 12 volts. As a result, this technology uses less energy than alkaline or lithium batteries [48]. However, unlike nickel–cadmium, this technology does not suffer from toxicity and it does not suffer much from the memory effect.

These batteries are recyclable with an expensive nickel content that makes them viable. Nickel–metal hydride technology saw a significant improvement in the mid-2010s; nickel–metal hydride batteries now have a good specific energy of 140 Wh/kg. There are only certain types of lithium-ion batteries that work better and a cost approximately equal to nickel–cadmium [48,54]. These batteries are, admittedly, less enduring than alkaline batteries, but they are enduring enough to compete with lithium technology with a life cycle of up to 3000 charge/discharge cycles. In addition, they do not suffer from any handling problems.

Thanks to a special electrolyte with improved ionic conductivity and very good hydride conductivity, Ni–MH batteries, unlike Li-ion batteries, can withstand low temperatures [55,56]. Thus, they keep their performance and reliability at sub-zero temperatures, with an especially excellent discharge capacity [57,58].

6.2.3. Solutions for Adapting Nickel–Metal Hydride (NiMH) Batteries to Cold Climates

Commercially available Ni–MH batteries are designed to function above −20 °C. However, according to manufacturer's manuals, they can only maintain less than 60% of their initial capacity at that temperature, though some experiments have found higher values. At −30 °C, the capacity of nickel–cadmium batteries drops to around 55%, while lead–acid batteries only retain about 30% of their capacity. For many years, typical lithium-ion batteries could only retain about 20% of their capacity at −30 °C, but recent improvements in electrolyte composition have enabled Li-ion batteries to retain up to 60% of their capacity at −30 °C, though for relatively low total capacities.

The rate of hydrogen migration from the bulk of the electrode to its surface, the kinetics of charge transfer reaction, and the mechanical stability and chemical corrosion of the negative electrode material determine the electrochemical performance of Ni–MH batteries. However, at temperatures below −20 °C, other considerations such as decreased conductivity, increased electrolyte viscosity, and the appearance of local concentration gradients should be considered to explain the mechanism of Ni–MH battery performance degradation. According to Karwowska et al. [59], the performance of an Ni–MH battery employing an electrolyte that can keep 81.7% of its capacity at −20 C is attainable when using a mixed binary NaOH/KOH 6 M electrolyte. Li et al. [60] designed a new HAS

(La0.95 Y0.05 Ni4.5 Mn0.4 Al0.35) that, compared to ordinary electrodes, has better kinetics and discharge performance at very low temperatures up to −45 °C. This can be explained by the excellent high-rate dischargeability (HRD) and low-temperature dischargeability (LTD) performances of the Co-free alloy attributed to the fast electrochemical reaction kinetics caused by the transfer of electrons/ions and the diffusion of hydrogen. The improvement and popularization of this new electrode may solve the problem of slow kinetics. Therefore, the design and material used in the manufacturing of Ni–MH batteries play key roles in their adaptation, i.e., maintaining their charging capacity, to cold climates with extremely low temperatures (up to −45 °C).

6.3. Lithium-Ion Batteries

Lithium-ion batteries use a reversible chemical reaction to circulate electrons and thus generate electrical energy [61]. Lithium is a metal whose atoms are composed of three electrons and three protons, among other elements. It has the characteristic of easily giving up an electron. It then becomes an ion, explaining the term lithium-ion. The battery has one or more cells, each with two electrodes. Generally, the cathode is made of cobalt oxide (CoO2), with some lithium, and the anode is made of graphite. The electrolyte contains a high concentration of lithium ions. The battery manufacturer carries out the first charge of the cells because it initiates the process and causes lithium ions to accumulate in the anode, thus creating a potential difference between the cathode and the anode [31,32,62,63].

The Li-ion battery has gained popularity due to its long-term viability, high working voltage, and low self-discharge rate [64–66]. The life of an Li-ion battery is quite long. With a very low self-discharge rate, high open-circuit voltage, and negligible memory effect, this battery has a higher power capacity than any other rechargeable battery without being bulky [67].

Today, the lithium-ion battery shares the market with nickel–cadmium and nickel–metal-hydride batteries. Older lead–acid batteries are now a niche market for the automotive industry and account for less than 2% of total sales in quantity [62].

However, with a higher voltage and better capacity-to-volume ratio, lithium-ion technology was a significant advance over the NiMH and NiCd technologies that preceded it [65]. Lithium-ions have made it possible to eliminate the memory effect that was a problem with NiMH and NiCd. If these batteries were only partially charged, they could no longer recover their full charge afterward [31].

In addition, research is underway to improve existing lithium-ion technology. First, lithium is associated with another material, such as fluorine, in the cathode to increase the voltage and power. Second, a few micrograms of graphene are added to the anode and cathode to raise the energy density of the cells by a few percent [31]. Additionally, in her thesis, Elise Nanini-Maury evaluated triethyl phosphate as an electrolyte solvent in lithium-ion batteries to marginally boost the electrolyte's oxidation potential [65].

6.3.1. Modeling and Optimization of Lithium-Ion Batteries According to the Application Domain

As mentioned in the previous paragraph, research avenues have been explored and others are underway to improve lithium-ion technology. This research concern the improvement of these technologies in different fields. For example, Patel [68] reported on modifying electrode chemistry to optimize energy density and capacity to reduce the price of Li-ion batteries in the automotive field. By changing the chemistry of the electrodes, the energy density of the batteries could be increased. The cathode composition has a significant impact on the ability of a battery. The current focus of research is on producing high-capacity and high-voltage cathode materials.

In his analysis, Patel [68] mentioned the usefulness of cobalt–lithium oxide cathodes and lithium–nickel–manganese–cobalt (NMC), which have energy densities of up to 190 and 180 Wh/kg, respectively. While cathodes occupy the focus of much of this research, scientists are also investigating new anode chemistries. Major battery companies, for example, aim to replace graphite anodes with silicon anodes, which have 10 times the charge storage capacity.

In contrast to Patel, who discussed research advances in electrode chemistry, Sarshar et al. [69] emphasized the need to predict or simulate the battery operation to optimize performance. Their work introduced two methodologies for the mathematical modeling and simulation of lithium-ion batteries: semi-empirical and multi-physics models. To forecast the capacity loss of the lithium-ion battery, they utilized an empirical model based on the power law idea for temperature and the square root of the number of cycles [70–73]. Model parameters were obtained based on the mean absolute square error of the experimental capacity prediction using the Levenberg–Marquardt algorithm [74]. As a result, the model could predict a commercial battery's maximum charge/discharge cycles. Additionally, the operation of a lithium-ion pocket cell was simulated using COMSOL multi-physics software [75] using simultaneous calculations of heat, mass, transfer, and electrochemical reactions. It follows from their study that empirical or semi-empirical equations are suitable when the battery designer needs to evaluate important parameters such as the lifetime of a battery. Moreover, the use of simulation tools reduces the cost of experiments for engineers and researchers.

Modeling Li-ion batteries is critically important to study battery behavior and enable power control in various applications [76]. There are many modeling approaches for batteries. These span from molecular dynamics models (using Monte Carlo simulation) through pseudo-dimensional, particle-scale physical, and multi-physics models to empirical models. Each method is different depending on the computation time for a multi-physics or empirical simulation.

Astaneh et al. [77] studied a methodology for the Li-ion battery simulations of an electric vehicle. The electrochemical model was inspired by the work of Doyle et al. [78], the mathematical formulation came from the work of Hosseinzadeh et al. [79], and the discretization of the electrodes and the separator came from the work of Smith et al. [80]. The simulations were performed using GT-AutoLion. the authors concluded that the methodology could provide a powerful tool for predicting and optimizing battery packs' electrical and thermal performance.

Park et al. [81] noted that statistical approaches to predicting the state of electric vehicle batteries generally depend on historical data measured by experiments and that approaches based on experimental value statistics are still inapplicable in real-world settings. They argued that an estimator that concomitantly estimates the state of charge (SOC) and the state of health (SOH) could compensate for the experimental value deficit. Their model combines the double extended Kalman filter (DEKF) with the autoregressive (AR) model to predict the SOH of Li-ion batteries. Their study concluded that their model is advantageous for estimating the battery state in real time.

Mao et al. [82] developed a method for accurately predicting the remaining service life in Li-ion batteries based on empirical ensemble mode decomposition (EEMD). They used a neural network with long- or short-term memory and a sliding time window (LSTM–STW) on the one hand and a Gaussian or sinusoidal function with a Levenberg–Marquardt algorithm (GS–LM) on the other. The main procedures of the proposed LSTM–STW–GS–LM fusion prediction method for battery RUL prediction are shown in Figure 13, divided into three steps. Two batteries of size 18,650 were used for the experimental results, which confirmed a high prediction accuracy of the remaining useful life of Li-ion batteries (Figure 14).

According to their findings, the suggested technique outperformed other common prediction methods in forecasting the remaining usable life of lithium batteries.

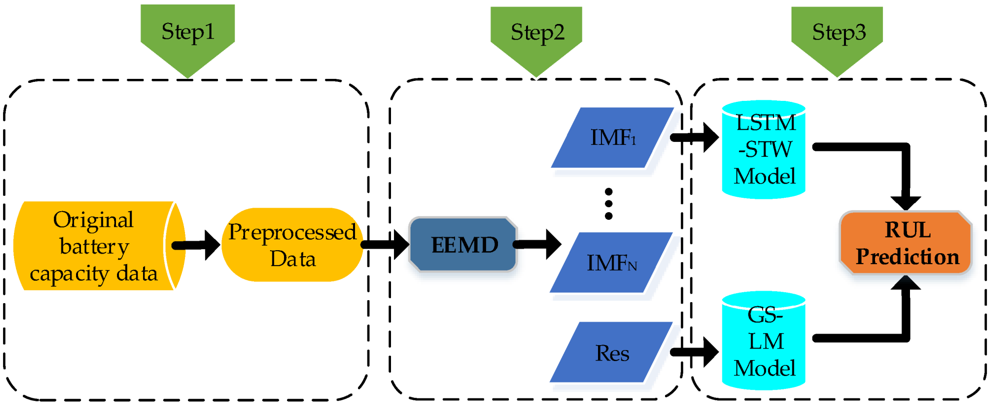

Figure 13. Battery RUL prediction structure based on LSTM–STW–GS–LM and EEMD [82].

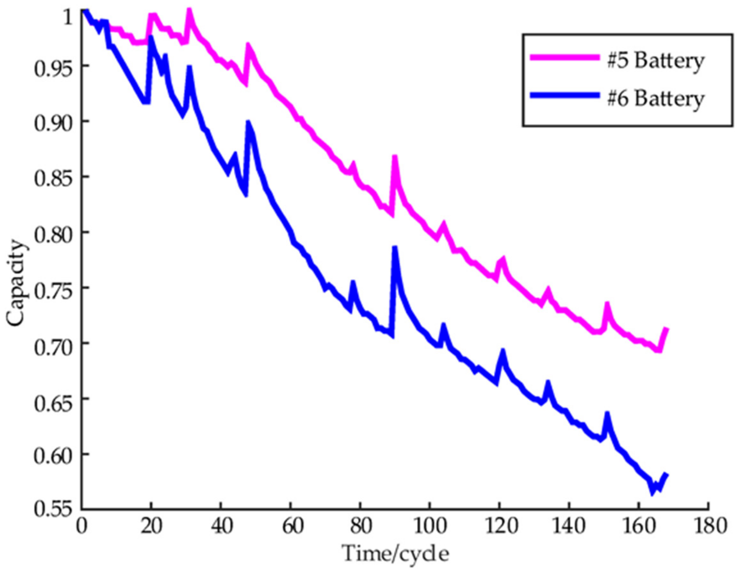

Figure 14. Degradation curves of the full charge capacity of two batteries (#5 and #6) [82].

6.3.2. Technical Characteristics of Charge–Discharge Rate of Li-Ion Batteries and Their Variation with Temperature

Among the known means of energy storage, the Li-ion battery has gained great popularity due to its longevity, high working voltage, and low self-discharge rate. However, certain factors internal to this battery will inevitably lead to a decrease in the number of lithium ions and an increase in the internal resistance of the battery. These include electro-chemical reactions and the increasing number of charge/discharge cycles. The direct consequence of all this will be the total loss of the battery [83]. Temperature variations also have a great influence on their autonomy. When the temperature falls below 0 °C, lithium-ion batteries lose significant capacity and power [84–89]. From −40 °C onwards, conventional Li-ion batteries retain only about 12% of their capacity at room temperature [90].

Piel and Bonenfant [91] experimented using an Li-ion battery at several temperatures to show whether the temperature impacted the battery's capacity. Their results, summarized in the diagram in Figure 15 [92], showed the electrical voltage (in volts) of an Li-ion battery as a function of its capacity (in milliampere hours) at several operating temperatures. Extreme temperatures (high or low) were found to influence the battery's ability to work for more extended periods. When the temperature equaled −20 °C, the capacity was the lowest. At −10 °C, the temperature played an important role in the electrical voltage, but it varied less than at −20 °C. Very high temperatures such as 60 or 40 °C were found to have less influence on the electrical voltage of the battery than temperatures below or equal to 0. The best electrical voltage was at 25 °C, as the battery's capacity was the highest at this temperature. They concluded by arguing that negative temperatures influence a battery's capacity more than very high temperatures. Furthermore, they reported that the optimal temperature for use was about 25 °C. Extreme temperatures influence the capacity (autonomy) of Li-ion batteries for the following reasons [91–96]:

- Cold affects the electromotive force of a battery (open circuit voltage). As a result, the battery's storage capacity is reduced.
- The conductivity of the electrolyte is effected by cold.
- Cold affects the kinetics of electrochemical reactions. It thus plays roles in capacity and the speed of the electrons to move in the electrolyte.

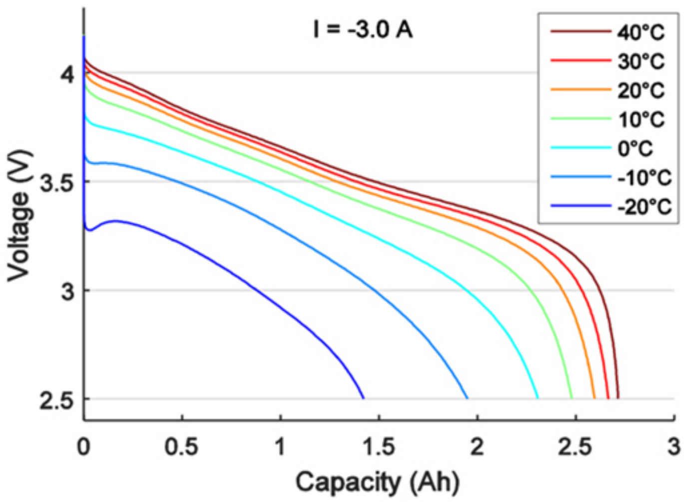

Figure 15. An Li-ion battery's electrical voltage based on its capability at various operating temperatures [92].

Zhang et al. [87] confirmed the results obtained by Piel and Bonenfant. They investigated the performance of a symmetrical Li-ion battery cell at cold temperatures. To reduce the complication of asymmetric cells, they investigated the temperature dependency of Li-ion electrode impedance using cells with graphite/graphite and cathode/cathode configurations. The processing of the cell impedance values identified the poor cycling performance at very cold temperatures. These impedance values also allowed us to understand the significant difference in cycling performance between the charge/discharge processes. A Tenney 942 series environmental oven provided a stable temperature environment for testing at different temperatures. Their results (shown in Figure 16) demonstrate a continuous decrease in operating capacity and voltage as a function of temperature. The discharge curves of an Li-ion cell at various temperatures are compared in this graphic. They ascribed the drop in operating voltage to the cell's higher electrical polarization, which is related to a decrease in the ionic conductivity of the electrolyte and the solid/electrolyte interface and a slowdown of the battery cell's electrochemical operations.

To see how electrolyte conductivity affects cell performance, they plotted electrolyte conductivity and relative capacitance against temperature (Figure 17). The electrolytic conductivity was found to continuously drop with temperature. On the other hand, there was a sharp drop in capacity when the temperature fell below the threshold of about −15 °C. This demonstrates that electrolytic conductivity is not the main constraint on Li-ion batteries' low-temperature performance.

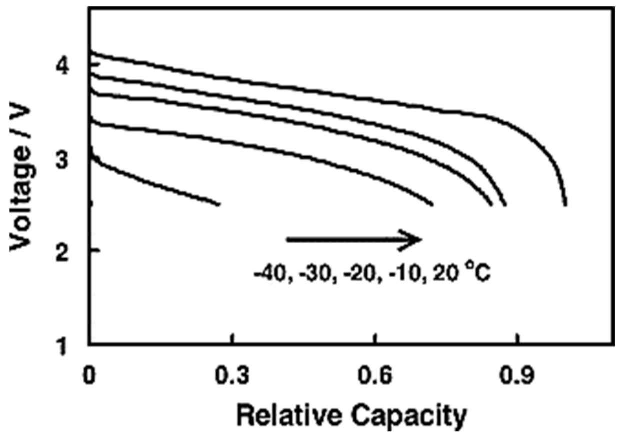

Figure 16. An Li-ion cell's discharge curves at various low temperatures [87].

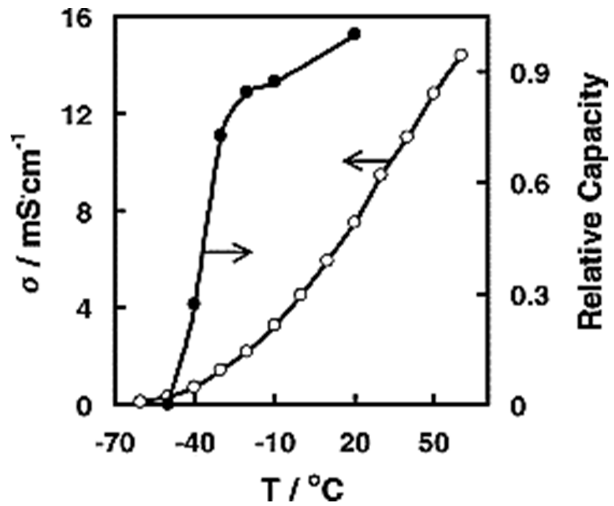

Figure 17. Temperature effects on the relative capacity of an Li-ion cell and the ionic conductivity of the electrolyte [87].

6.3.3. Solutions for Adapting Li-Ion Batteries to Cold Climates

Advanced lithium-ion battery technology is now widely employed in various applications, including telecommunication, personal transportation (such as e-bikes and scooters), automotive, aerospace, grid, and stationary applications. The fundamental and operational constraints of Li-ion batteries can be divided into two categories: intrinsic and operation restrictions. The intrinsic restrictions are due to inescapable material-related constraints regardless of battery usage, e.g., the electrolyte's transport properties and charge transfer rates inside the electrode materials. Meanwhile, operational constraints are determined by how actively a cell is cycled at a given SOC and temperature. As a result, it is well-understood that the issues faced by Li-ion batteries in low-temperature environments are related to operational constraints. Previous investigations have proven that the rapid charging of Li-ion batteries at subzero temperatures could potentially affect the batteries and contribute to their degradation [12]. For example, when Li-ion batteries are operated at −10 °C rather than 20 °C, their capacity is reduced by up to 95%. When Li-ion battery storage systems fail to fulfill load demand due to aging behavior associated with their operation in extremely cold conditions, this capacity drop is unsatisfactory in many applications. Performance loss in cold temperatures is explained by a considerable increase in internal resistance, which raises the cell's internal temperature (warming cells) and may eventually damage the Li-ion battery. As a result, enhanced thermal behavior studies, updated electrode materials, improved charging/discharging arrangements, and complete battery thermal management are all suggested as ways to increase Li-ion performance in a cold climate.

A battery's performance mainly depends on its electrodes and electrolyte. At low temperatures, the electrolyte becomes viscous and can freeze, greatly reducing its ability to conduct lithium ions to the electrodes. Dong et al. [90] used an electrolyte made of ethyl acetate, a solvent that freezes at a temperature of −84 °C and thus effectively retains its ability to conduct charges when cold. The ethyl acetate electrolyte has the particularity to keep a good ionic conductivity of about 0.2 $mS.cm^{-1}$ (millisiemens per centimeter) at a very low temperature of −70 °C. Additionally, to improve the design of the electrodes, they used organic compounds that, unlike conventional electrodes made of metal oxide and graphite, can collect lithium ions in their matrix at ultra-cold temperatures. Therefore, the batteries are operable and effectively rechargeable down to −70 °C.

Figure 18A shows that resistance to ethyl acetate electrolyte grows, like any other electrolyte, with decreasing temperature. Figure 18B shows that the ethyl acetate-based electrolyte still has a good ionic conductivity below −30 °C while that of the commercial electrolyte drops drastically.

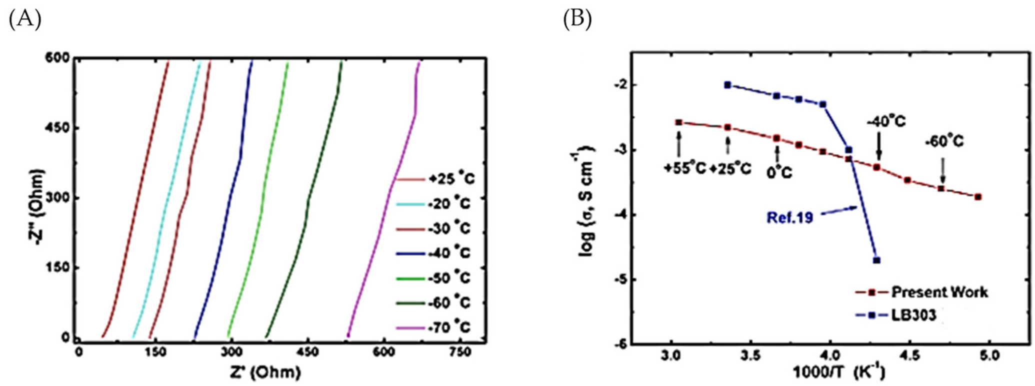

Figure 18. Electrochemical characterization of ethyl acetate-based electrolyte [90]. (**A**) Nyquist plot obtained from electrochemical impedance spectroscopy investigation for the ethyl acetate-based electrolyte at different temperatures. (**B**) Ion conductivity of the electrolyte calculated from a Nyquist plot at different temperatures and comparison with commonly used electrolyte.

Other approaches have been developed to evaluate the characteristics of Li-ion batteries operating in very cold climate conditions. These include the development of electrolyte additives to improve performance in very cold climates or even to maintain batteries at mild temperatures by heating [97,98], which seem to work well. However, recharging batteries at very cold temperatures remains problematic [90].

6.4. Lithium Polymer Batteries

Lithium polymer (Li-Po) batteries, which first appeared in the late 1970s, are a variant of lithium-ion technology. Originally, the electrolyte in these batteries was a dry solid polymer. These batteries have an energy density and characteristics roughly similar to lithium-ion batteries and are easy to produce. They are widely used in model making for weight reasons. Despite its poor conductivity due to its high internal resistance, Li-Po technology is slightly more stable than lithium-ion, but it is also more expensive. Not only are Li-Po batteries more durable than other rechargeable batteries, but they also have a relatively low self-discharge rate. Nowadays, the problem of poor conductivity has been relatively solved with the addition of polymer gel electrolyte to dry polymer electrolyte. This will make them less dangerous and suitable for high-current applications with high discharge rates [24]. As a result, polymer gel electrolytes have potential for high-performance lithium and non-lithium batteries [99].

Additionally, an Li-Po battery has the same morphology as any rechargeable battery (Figure 19) [99].

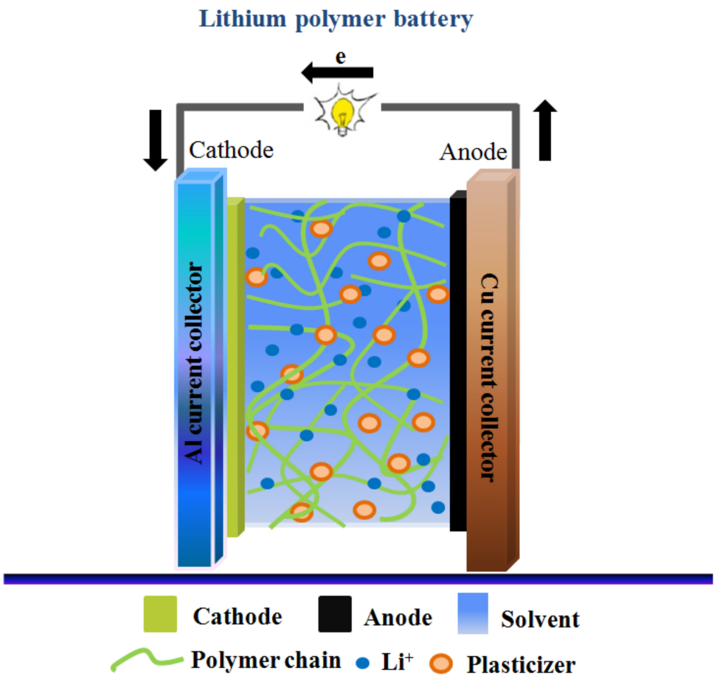

Figure 19. Diagram of an Li-Po battery based on gel polymer electrolyte [99].

6.4.1. Technical Characteristics of Charge–Discharge Rate of Lithium Polymer Batteries and Their Variation with Temperature

Despite the many advantages of gelled Li-Po batteries that make them very practical in portable electronics, they face the same challenge of good performance at very cold temperatures and/or high-current pulses as other devices [100].

6.4.2. Solutions for Adapting Lithium Polymer Batteries to Cold Climates

Optimizing both the electrolyte compositions and techniques for creating gelled polymer electrolytes and electrode coatings can improve the low-temperature performance of gelled Li-Po batteries. This was demonstrated in the work of Xinga and Sugiyama [100], who were able to increase Li-Po battery performance at temperatures as low as −20 °C.

Smart et al. [101] utilized this process to create prototypes of gelled Li-Po cells that performed well at temperatures as low as −60 °C.

Other work has shown that multi-component electrolytes, particularly those low in ethylene carbonate, have improved the performance of Li-Po batteries at very cold temperatures [102,103]. Aliphatic esters have also been found to be suitable solvents for enhancing the properties of gelled polymer electrolytes at low temperatures [85,86,94,104–106].

7. Containerized Solutions for Batteries

Integrated containers are designed to facilitate energy storage using lithium-ion batteries to cope with the harsh environmental conditions of Nordic countries (Figure 20 [107]). Thus, Saft, a 100% Total subsidiary, plans to install a 103 MWh unit [108,109]. This storage capacity will be divided into four units of about 25 MWh each, all of which were to be commissioned by 2022. The first will be installed in Mardyck, on the premises of Total's Etablissement des Flandres, located in the port area of Dunkirk (Nord). It will be the largest lithium-ion storage system in France and help secure its power grid. The Dunkirk installation will consist of 11 integrated containers, each with a capacity of 2.3 MWh, designed and manufactured at Total's subsidiary Saft's production site in Bordeaux (Aquitaine). This installation represents an investment of approximately 15 million euros.

Figure 20. Integrated containerized solutions of 2.3 MWh each, presented by Saft (adapted from [107]).

Using the same technology, Saft has announced the supply of three containers called Intensium Max 20 High Energy to TuuliWatti, a Finnish wind energy company [110,111]. This lithium-ion energy storage device will provide frequency-management services to improve the integration of renewable energy produced by a 21 MW wind farm in Viinamäki, Northwest Finland, into the electricity grid. In addition, it will optimize wind energy while providing the power needed for backup and cold start. The Nordic countries' largest lithium-ion storage system has a storage capacity of 6.6 MWh and a power output of 5.6 MW, allowing it to offer frequency control over a 15-year period. Three integrated containers of 2.2 MWh each make up this system.

Megawatt-scale containerized systems for grids and renewable energy sources are very flexible. These Li-ion containerized energy storage systems significantly reduce the effects of intermittency of renewable energy sources such as solar and wind. The Intensium® Max 20 High Energy, which can conveniently operate without a pilot at temperatures ranging from −35 to 55 °C, is the ideal solution for large-scale electrical energy storage for grids, renewables, and industries [112].

In Canada, the Calgary-based company Eneon-ES, created by combining the two companies Tundra Process Solutions and Canadian Energy, has also launched battery energy storage systems [113], which have also been integrated into used, 20–40-foot maritime containers that were refurbished under strict safety protocol and fire protection guidelines. The combination of energy storage and renewable energy integration provides off-grid electricity to hard-to-reach communities, reducing dependence on diesel consumption, as well as storage and delivery costs. Eneon-ES activities have expanded across North America, including Massachusetts, where a customer requested that 1.2 MWh of storage be condensed into a 20-foot sea container while maximizing solar power production from an oversized solar array to provide off-grid power to four semi-mobile solar-powered research stations in the Arctic Circle. Hydro-Québec, through its subsidiary EVLO, has also launched containerized energy storage systems for the power generation, transmission, and distribution sectors [114]. EVLO modules are huge batteries installed in containers using a lithium iron phosphate chemical composition. More secure than traditional batteries, they are also 99% recyclable. Energy storage containers are gradually becoming the norm for Canadian companies, giving them a head start in the field.

8. Discussion

Electrical energy storage using lead–acid batteries is very mature and widely used to store public services energy. Lead–acid battery technological advancements have extended cycle life in both deep and shallow cycle applications. Furthermore, lead–acid batteries have a longer lifespan than other battery types and no memory effect [36]. However, inexpensive lead–acid batteries suffer from a high weight, short runtime, cold sensitivity and transportation difficulty due to their liquid acid. To optimize these batteries, it is necessary to avoid completely discharging them and storing them charged [115].

Nickel–cadmium (Ni–Cad) batteries are lighter than lead–acid batteries and relatively cheap. They have a medium autonomy. Nickel–cadmium batteries are suitable for very low temperatures. However, their extremely poisonous cadmium is known to be less suited for disposal, particularly in landfills, and this environmental concern has remained a significant disadvantage. Nickel–cadmium batteries thus contain toxic materials whose distribution and disposal are highly regulated in many countries. In addition, they have a low specific energy (up to 80 Wh/kg), compared to more contemporary alternatives based on nickel metal hydride and lithium, and a high self-discharge rate (10% per month), compared to lithium, alkaline, and lead–acid batteries. There is also the myth of the memory effect that hangs over this technology. To optimize these batteries, they must be stored discharged.

Ni–MH batteries are similar to Ni–Cad batteries. They do not suffer much from the memory effect and have better autonomy. They are more expensive but are subject to the phenomenon of self-discharge.

Lithium batteries (Li-ion or Li-Po) are light and have good autonomy. They do not suffer from memory effects and have various shapes. To optimize these batteries, they should be stored lightly charged at a temperature of about 20 °C.

The selection criteria are entirely different in stationary applications, such as the mass storage of electricity from renewable energies or the electrification of residential areas. Indeed, the notions of Wh/kg or Wh/L lose importance due to the absence of mass or volume constraints in these stationary applications. Therefore, in addition to safety, the selection criteria are cyclability (durability) and cost [27].

Li-ion batteries are well-suited for energy storage for renewable energy installations because of their unmatched performance (see Table 4 for comparisons of technical parameters of different electrochemical energy storage systems). Their inability to withstand very low temperatures can be solved by developing containerized battery solutions.

Table 4. Comparison of technical characteristics of accumulators (adapted from [116]).

	Lead	**Ni/Cd**	**Ni/MH**	**Li Ion**	**Li Polymer**
Specific energy (Wh/kg)	30–50	45–80	60–110	150–190	150–190
Energy density (Wh/liter)	75–120	80–150	220–330	220–330	220–330
Peak power (W/kg)	Up to 700	—-	Up to 900	Up to 1500	Up to 250
Number of cycles (charge/discharge)	400–1200	2000	1500	500–1000	200–300
Self-discharge per month	5%	20%	30%	10%	10%
Nominal voltage of an element	2 V	1.2 V	1.2 V	3.6 V	3.7 V
Operating temperature range	−20 to 60° C	−40 to 60 °C	−20 to 60 °C	−20 to 60 °C	0 to 60 °C
Advantages	Low cost	Reliability Cold performance	Very good energy density	Excellent energy and power	Thin batteries possible
Disadvantages	Low energy Sudden death	Relatively low energy Toxicity	Cost of basic materials Behavior in temperature	Safety of large elements Cost	Cold performance Cost
Indicative Costs (€/kWh)	200 to 250	600	1500 to 2000	2000	1500 to 2000

9. Conclusions

The use of storage systems can significantly reduce the constraints imposed on renewable energy in off-grid installations. The use of energy storage has increased renewable energy integration in Canada's North. Storage systems allow for the storage of the energy produced at the output of renewable energy installations, making it available for subsequent use when the renewable resource is no longer sufficient.

Rechargeable batteries play an important role in allowing for the greater penetration of intermittent renewable energy sources in distant areas where they are the principal energy storage mode. However, the very cold climate of remote areas represents a barrier to the optimal operation of these batteries.

Electrochemical energy storage is a major strategic issue on a global scale. Considerable research and development efforts are currently being conducted in many countries to develop more efficient batteries, with multiple objectives including improvements of the autonomy of portable systems, electric vehicles, and hybrid vehicles and large-scale storage for electrical grids. Lithium-ion technology has been the most important advance among the developed and widespread electrochemical technologies such as lead–acid, Ni–Cd, Ni–MH, Li-ion, and Li-Po batteries. The Li-ion battery has grown in popularity because of its longevity, high working voltage, and low self-discharge rate. It has a higher charge density and lower weight than similar rechargeable batteries. As a result, it features a large power capacity while being compact and having a low self-discharge rate and little memory effect. In addition, it has a greater open-circuit voltage than lead–acid, nickel–metal hydride, and nickel–cadmium aqueous batteries. Typically, an Li-ion battery can withstand hundreds of charge–discharge cycles.

There is now research being conducted to change the electrodes' chemistry to enhance the energy capacity and lower the cost of these batteries. Several Li-ion battery models have been created to research battery behavior and enable power regulation in various applications. However, researchers are facing some difficulties. For example, it is uncertain which lithium-ion battery chemistry will enhance energy capacity while decreasing prices.

Although some researchers have attempted to increase low-temperature performance through advances in power battery materials, it is difficult, and no definite answer has been found thus far. The development of containerized battery solutions, on the other hand, may make it easier to use Li-ion batteries in challenging environments such as extremely cold climes.

While traditional Li-ion batteries (for their stored energy density) and supercapacitors (for their power density) can already cover the majority of the electricity storage markets, alternative systems, such as lithium–sulfur, metal–air, and sodium–ion batteries, are being developed [27].

Author Contributions: Conceptualization, Y.A.; Data curation, Y.A.; Formal analysis, Y.A.; Funding acquisition, A.I.; Investigation, Y.A.; Methodology, Y.A.; Project administration, A.I.; Resources, A.I.; Supervision, A.I.; Validation, A.I.; Visualization, Y.A.; Writing – original draft, Y.A.; Writing – review & editing, M.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The study did not report any data.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

PJ	Petajoule
YT	Yukon
NT	Northwest Territories
NU	Nunavut
QC	Quebec
MB	Manitoba
AB	Alerta
BC	British Columbia
NL	Newfoundland and Labrador
NB	New Brunswick
SK	Saskatchewan
NS	Nova Scotia
PE	Prince Edward Island
ON	Ontario

References

1. Alcen Corporate Foundation for Knowledge of Energies. BP Presents Key Energy Figures around the World. Available online: https://www.connaissancedesenergies.org/bp-statistical-review-world-energy-2018-les-chiffres-cles-de-lenergie-dans-le-monde-180614 (accessed on 23 September 2019).
2. Canada Energy Regulator. Provincial and Territorial Energy Profiles—Quebec. Available online: https://www.cer-rec.gc.ca/fr/donnees-analyse/marches-energetiques/profils-energetiques-provinces-territoires/profils-energetiques-provinces-territoires-quebec.html (accessed on 6 October 2021).
3. Turner, A.; Guillaud, C. The application of energy management systems to remote northern communities. In *Energy Developments: New Forms, Renewables, Conservation*; The Global Energy Forum: Regina, SK, Canada, 1984; pp. 935–940. [CrossRef]
4. Majorowicz, J.; Grasby, S.E. Geothermal energy for northern Canada: Is it economical? *Nat. Resour. Res.* **2014**, *23*, 159–173. [CrossRef]
5. Giordano, N.; Kanzari, I.; Miranda, M.; Dezayes, C.; Raymond, J. Shallow geothermal resource assessments for the northern community of Kuujjuaq, Québec, Canada. In Proceedings of the IGCP636 Annual Meeting, Santiago de Chile, Chile, 21 November 2017; pp. 1–3.
6. Serra, L. *Barriers to the Implementation of Renewable Energy Projects in Off-Grid Communities in Canada's Northern Regions*; Masters in Environment, University of Sherbrooke: Sherbrooke, QC, Canada, 2011.
7. Longo, M.; Yaïci, W.; Foiadelli, F. Hybrid Renewable Energy System with Storage for Electrification–Case Study of Remote Northern Community in Canada. *Int. J. Smart Grid-Ijsmartgrid* **2019**, *3*, 63–72.
8. Belzile, P.; Comeau, F.A.; Raymond, J.; Lamarche, L. *Technology Review: Energy Efficiency and Renewable Energies in Northern Quebec*; No. R1716; INRS, Water Earth Environment Center Quebec City: Quebec, QC, Canada, 2017; pp. 1–38.
9. Zharan, K.; Bongaerts, J.C. Survey on Integrating of Renewable Energy into the Mining Industry. *J. Environ. Account. Manag.* **2018**, *6*, 149–165. [CrossRef]
10. Vyhmeister, E.; Muñoz, C.A.; Miquel, J.M.B.; Moya, J.P.; Guerra, C.F.; Rodriguez, L.; Godoy-Faúndez, A.; Higueras, P.; Clemente-Jul, C.; Valdes-Gonzalez, H.; et al. A combined photovoltaic and novel renewable energy system: An optimized techno-economic analysis for mining industry applications. *J. Clean. Prod.* **2017**, *149*, 999–1010. [CrossRef]
11. Slavin, A. New renewable energy for mine project-LAMGOLD Essakane to benefit from largest hybrid plant in Africa (Case Study). *Energy Mines* **2017**, *3*, 547–559.
12. Chen, H.; Cong, T.N.; Yang, W.; Tan, C.; Li, Y.; Ding, Y. Progress in electrical energy storage system: A critical review. *Prog. Nat. Sci.* **2009**, *19*, 291–312. [CrossRef]
13. Taylor, T. Energy storage. In *EPJ Web of Conferences 2018*; EDP Sciences: Les Ulis, France, 2018; Volume 189, p. 00009. [CrossRef]
14. Dimitriev, O.; Yoshida, T.; Sun, H. Principles of solar energy storage. *Energy Storage* **2020**, *2*, e96. [CrossRef]
15. Canada Energy Regulator. Market Snapshot: Understanding the High Energy Costs in Northern Canada. Available online: https://www.cer-rec.gc.ca/fr/donnees-analyse/marches-energetiques/apercu-marches/2017/apercu-marche-comprendre-couts-eleves-lenergie-dans-nord-canadien.html (accessed on 23 October 2020).
16. Allard, M.; Lemay, M. Nunavik and Nunatsiavut: From science to policy. In *An Integrated Regional Impact Study (IRIS) of Climate Change and Modernization*; ArcticNet: Quebec, QC, Canada, 2012; p. 303.
17. Canada Energy Regulator. Provincial and Territorial Energy Profiles—Yukon. Available online: https://www.cer-rec.gc.ca/en/data-analysis/energy-markets/provincial-territorial-energy-profiles/provincial-territorial-energy-profiles-yukon.html (accessed on 6 October 2021).
18. Thompson, S.; Duggirala, B. The feasibility of renewable energies at an off-grid community in Canada. *Renew. Sustain. Energy Rev.* **2009**, *13*, 2740–2745. [CrossRef]

19. Shu, L.; Qiu, G.; Hu, Q.; Jiang, X.; McClure, G.; Liu, Y. Numerical and experimental investigation of threshold de-icing heat flux of wind turbine. *J. Wind Eng. Ind. Aerodyn.* **2018**, *174*, 296–302. [CrossRef]
20. Ibrahim, G.; Pope, K.; Muzychka, Y. Effects of blade design on ice accretion for horizontal axis wind turbines. *J. Wind Eng. Ind. Aerodyn.* **2018**, *173*, 39–52. [CrossRef]
21. Shu, L.; Li, H.; Hu, Q.; Jiang, X.; Qiu, G.; McClure, G.; Yang, H. Study of ice accretion feature and power characteristics of wind turbines at natural icing environment. *Cold Reg. Sci. Technol.* **2018**, *147*, 45–54. [CrossRef]
22. Ibrahim, H.; Ilinca, A.; Perron, J. Energy storage systems—Characteristics and comparisons. *Renew. Sustain. Energy Rev.* **2008**, *12*, 1221–1250. [CrossRef]
23. Allart, D. Management and Electrothermal Modeling of Lithium-Ion Batteries. Ph.D. Thesis, Normandy University, Caen, France, 2017.
24. Hossain, E.; Faruque, H.M.R.; Sunny, M.; Haque, S.; Mohammad, N.; Nawar, N. A Comprehensive Review on Energy Storage Systems: Types, Comparison, Current Scenario, Applications, Barriers, and Potential Solutions, Policies, and Future Prospects. *Energies* **2020**, *13*, 3651. [CrossRef]
25. Zhang, H.; Sun, C. Cost-effective iron-based aqueous redox flow batteries for large-scale energy storage application: A review. *J. Power Sources* **2021**, *493*, 229445. [CrossRef]
26. Ibrahim, H.; Ilinca, A.; Perron, J. Comparison and analysis of different energy storage techniques based on their performance index. In Proceedings of the 2007 IEEE Canada Electrical Power Conference, Montréal, QC, Canada, 25–26 October 2007; IEEE: New York, NY, USA, 2008; pp. 393–398. [CrossRef]
27. Simon, P. Electrochemical energy storage: Principles, applications and future challenges. In *Annals of Mines-Responsibility and Environment*; FFE: Lancaster, TX, USA, 2015; pp. 67–72. [CrossRef]
28. Nadeem, F.; Hussain, S.S.; Tiwari, P.K.; Goswami, A.K.; Ustun, T.S. Comparative review of energy storage systems, their roles, and impacts on future power systems. *IEEE Access* **2018**, *7*, 4555–4585. [CrossRef]
29. Van den Bossche, P.; Vergels, F.; Van Mierlo, J.; Matheys, J.; Van Autenboer, W. SUBAT: An assessment of sustainable battery technology. *J. Power Sources* **2006**, *162*, 913–919. [CrossRef]
30. Prensier, J.L.; Lusseau, C. Principle of Operation and Components of a Battery. Available online: https://eduscol.education.fr/sti/sites/eduscol.education.fr.sti/files/ressources/pedagogiques/6107/6107-annexe-principe-de-fonctionnement-et-constituants-dune-batterie-ens.pdf (accessed on 21 December 2020).
31. Bedin, F. How Does a Lithium-Ion Battery Work? Available online: https://www.01net.com/actualites/comment-fonctionne-une-batterie-lithium-ion-1378434.html#:~:text=Le%20fonctionnement%20d\T1\textquoterightune%20batterie%20Lithium%2DIon&text=La%20batterie%20comporte%20un%20ou,dot%C3%A9s%20chacun%20de%20deux%20%C3%A9lectrodes.&text=En%20cons%C3%A9quence%2C%20les%20ions%20de,pour%20%C3%A9quilibrer%20la%20charge%20%C3%A9lectrique (accessed on 30 June 2020).
32. Vallverdu, G. *Principe de Fonctionnement des Batteries au Lithium*; University of Pau and the Adour Countries: Pau, France, 2011.
33. Chapman, B. Lets Talk Science. Available online: https://letstalkscience.ca/educational-resources/stem-in-context/how-does-a-lithium-ion-battery-work (accessed on 6 February 2022).
34. Delaille, A. Development of Methods for Evaluating the State of Charge and the State of Health of Batteries Used in Photovoltaic Systems. Ph.D. Thesis, Paris VI University, Paris, France, 2006.
35. Karoui, F. Optimization of Management Strategies for Lead-Acid Batteries Used in Photovoltaic Systems. Ph.D. Thesis, National Polytechnic Institute of Grenoble-INPG, Grenoble, France, 2007.
36. May, G.J.; Davidson, A.; Monahov, B. Lead batteries for utility energy storage: A review. *J. Energy Storage* **2018**, *15*, 145–157. [CrossRef]
37. Solar-Battery. Principle of Operation of a Lead Acid Battery. Available online: https://www.batterie-solaire.com/Accumulateur-plomb-principe-fonctionnement.htm (accessed on 29 December 2020).
38. Noël, J. Optimization of the Life of Lead Acid Batteries. Victron Energy Documents. Available online: https://www.victronenergy.fr/upload/documents/Optimiser-la-vie-des-batteries-plomb-Le%C3%A7on-V02-Bis.pdf (accessed on 14 February 2021).
39. GUIDEnR Photovoltaïque. Photovoltaic Information. Available online: http://www.photovoltaique.guidenr.fr/cours-photovoltaique-autonome/I_effet-temperature-capacite-batterie.php (accessed on 15 February 2021).
40. Solar-Battery. Mechanisms of Degradation of Lead Acid Batteries. Available online: https://www.batterie-solaire.com/Mecanismes-degradation-batterie-plomb.htm (accessed on 27 February 2021).
41. Wang, Y.; Zhang, P.; Li, Y.L.; Li, L.; Liang, J.Q.; Gao, Y.; Zhang, H.D.; Sun, W. The Influence of Carbon Material on the Low-Temperature Performance of Lead-Acid Battery. In *Engineering Materials Key*; Shixuan, X., Translator; Tech Publications Ltd: Bäch SZ, Switzerland, 2020; Volume 842, pp. 236–241.
42. Giess, H. Performance of VRLA cells and monoblocs under arctic conditions. In Proceedings of the 24th Annual International Telecommunications Energy Conference, Montreal, QC, Canada, 29 September–3 October 2002; IEEE: New York, NY, USA, 2002; pp. 55–60. [CrossRef]
43. Penn East of Canada. Exceptional Batteries for the Canadian Market. Available online: https://www.eastpenncan-ada.com/FR/technologie-agm.html (accessed on 1 March 2021).
44. Moseley, P.T. Improving the valve-regulated lead–acid battery. *J. Power Sources* **2000**, *88*, 71–77. [CrossRef]
45. Häring, P.; Giess, H. Performance of a VRLA battery in an arctic environment. *J. Power Sources* **2003**, *116*, 257–262. [CrossRef]

46. Brodd, R. Nickel-Based Battery Systems. In *Batteries for Sustainability*; Springer: New York, NY, USA, 2013; pp. 423–443. [CrossRef]
47. Huang, Z.; Du, G. Nickel-based batteries for medium-and large-scale energy storage. In *Advances in Batteries for Medium and Large-Scale Energy Storage*; Elsevier: Amsterdam, The Netherlands; Woodhead Publishing: Sawston, UK, 2015; pp. 73–90. [CrossRef]
48. The BatteryGuy.com Knowledge Base. What Are Nickel-Based Batteries. Available online: https://batteryguy.com/kb/knowledge-base/what-are-nickel-based-batteries/ (accessed on 1 March 2021).
49. SolarReviews. The Best Uses for Nickel Cadmium (Ni-Cd) Batteries. Available online: https://www.solarreviews.com/blog/best-uses-for-nickel-cadmium-batteries (accessed on 6 October 2021).
50. Petrovic, S. Nickel–Cadmium Batteries. In *Battery Technology Crash Course*; Springer: Cham, Switzerland, 2021; pp. 73–88. [CrossRef]
51. Omar, N.; Firouz, Y.; Monem, M.A.; Samba, A.; Gualous, H.; Coosemans, T.; Van Den Bossche, P.; Van Mierlo, J. Analysis of nickel-based battery technologies for hybrid and electric vehicles. In *Reference Module in Chemistry, Molecular Sciences and Chemical Engineering*; Elsevier: Amsterdam, The Netherlands, 2014; pp. 1–12.
52. Dell, R.; Rand, D.A.J. *Understanding Batteries*; Royal Society of Chemistry: London, UK, 2001; pp. 1–60. [CrossRef]
53. Jade-Technology. The NiMH Battery: Advantages, Disadvantages, Applications. Available online: https://www.jade-technologie.com/avantages-accus-nimh-nickel-metal-hydrure/ (accessed on 19 April 2021).
54. Karwowska, M.; Jaron, T.; Fijalkowski, K.J.; Leszczynski, P.J.; Rogulski, Z.; Czerwinski, A. Influence of electrolyte composition and temperature on behaviour of AB5 hydrogen storage alloy used as negative electrode in Ni–MH batteries. *J. Power Sources* **2014**, *263*, 304–309. [CrossRef]
55. Sides, C.R.; Martin, C.R. Nanostructured Electrodes and the Low-Temperature Performance of Li-Ion Batteries. *Adv. Mater.* **2005**, *17*, 125–128. [CrossRef]
56. Rodrigues, M.T.F.; Babu, G.; Gullapalli, H.; Kalaga, K.; Sayed, F.N.; Kato, K.; Joyner, J.; Ajayan, P.M. A materials perspective on Li-ion batteries at extreme temperatures. *Nat. Energy* **2017**, *2*, 1–14. [CrossRef]
57. Zhou, W.; Zhu, D.; Tang, Z.; Wu, C.; Huang, L.; Ma, Z.; Chen, Y. Improvement in low-temperature and instantaneous high-rate output performance of Al-free AB5-type hydrogen storage alloy for negative electrode in Ni/MH battery: Effect of thermodynamic and kinetic regulation via partial Mn substituting. *J. Power Sources* **2017**, *343*, 11–21. [CrossRef]
58. Yang, H.; Chen, Y.; Tao, M.; Wu, C.; Shao, J.; Deng, G. Low temperature electrochemical properties of $LaNi_{4.6-x}Mn_{0.4}M_x$ (M = Fe or Co) and effect of oxide layer on EIS responses in metal hydride electrodes. *Electrochim. Acta* **2010**, *55*, 648–655. [CrossRef]
59. Karwowska, M.; Fijalkowski, K.; Czerwiński, A. Low Temperature Characteristics of Hydrogen Storage Alloy LaMm-Ni4.1Al0.3Mn0.4Co0.45 for Ni-MH Batteries. *Materials* **2019**, *12*, 4220. [CrossRef]
60. Li, M.M.; Wang, C.C.; Yang, C.C. Development of high-performance hydrogen storage alloys for applications in nickel-metal hydride batteries at ultra-low temperature. *J. Power Sources* **2021**, *491*, 229585. [CrossRef]
61. Hemery, C.V. Studies of Thermal Phenomena in Li-Ion Batteries. Ph.D. Thesis, University of Grenoble, Grenoble, France, 2013.
62. Lazzari, O. *The Lithium-Ion Accumulators in Japan*; National Center INIS: Gif-sur-Yvette, France, 2006.
63. Xie, J.; Lu, Y.C. A retrospective on lithium-ion batteries. *Nat. Commun.* **2020**, *11*, 2499. [CrossRef]
64. Mu, D.; Jiang, J.; Zhang, C. Online semiparametric identification of Lithium-Ion batteries using the wavelet-based partially linear battery model. *Energies* **2013**, *6*, 2583–2604. [CrossRef]
65. Nanini-Maury, E. Formulation of High Potential Electrolytes for the Characterization of Innovative Positive Electrodes: Lithium-Ion Batteries for Electric Vehicles. Ph.D. Thesis, Paris VI University, Pierre and Marie Curie University, Paris, France, 2014.
66. Long, L.; Wang, S.; Xiao, M.; Meng, Y. Polymer electrolytes for lithium polymer batteries. *J. Mater. Chem. A* **2016**, *4*, 10038–10069. [CrossRef]
67. Chung, S.Y.; Bloking, J.T.; Chiang, Y.M. Electronically conductive phospho-olivines as lithium storage electrodes. *Nat. Mater.* **2002**, *1*, 123–128. [CrossRef]
68. Patel, P. *Improving the Lithium-Ion Battery*; ACS Publications: Washington, DC, USA, 2015. Available online: https://pubs.acs.org/doi/10.1021/acscentsci.5b00223 (accessed on 20 February 2020).
69. Sarshar, M.; Zarei-Jelyani, M.; Babaiee, M. Application of semi empirical and multiphysics models in simulating lithium ion battery operation. In Proceedings of the 10th International Chemical Engineering Congress and Exhibition, Isfahan, Iran, 6–10 May 2018.
70. Liu, D.; Wang, H.; Peng, Y.; Xie, W.; Liao, H. Satellite lithium-ion battery remaining cycle life prediction with novel indirect health indicator extraction. *Energies* **2013**, *6*, 3654–3668. [CrossRef]
71. Rong, P.; Pedram, M. An analytical model for predicting the remaining battery capacity of lithium-ion batteries. *IEEE Trans. Very Large Scale Integr. (VLSI) Syst.* **2006**, *14*, 441–451. [CrossRef]
72. Sarasketa-Zabala, E.; Martinez-Laserna, E.; Berecibar, M.; Gandiaga, I.; Rodriguez-Martinez, L.; Villarreal, I. Realistic lifetime prediction approach for Li-ion batteries. *Appl. Energy* **2016**, *162*, 839–852. [CrossRef]
73. Abe, M.; Nishimura, K.; Seki, E.; Haruna, H.; Hirasawa, T.; Ito, S.; Yoshiura, T. Lifetime prediction for heavy-duty industrial lithium-ion batteries that enables highly reliable system design. *Hitachi Rev.* **2012**, *61*, 259–263.
74. Marquardt, D.W. An algorithm for least-squares estimation of nonlinear parameters. *J. Soc. Ind. Appl. Math.* **1963**, *11*, 431–441. [CrossRef]

75. Multiphysics, C. *Introduction to COMSOL Multiphysics Version 5.3*; COMSOL Multiphysics: Burlington, MA, USA, 1998; Volume 9, p. 2018.
76. Jin, N.; Danilov, D.L.; Van den Hof, P.M.; Donkers, M. Parameter estimation of an electrochemistry-based lithium-ion battery model using a two-step procedure and a parameter sensitivity analysis. *Int. J. Energy Res.* **2018**, *42*, 2417–2430. [CrossRef]
77. Astaneh, M.; Andric, J.; Löfdahl, L.; Maggiolo, D.; Stopp, P.; Moghaddam, M.; Chapuis, M.; Ström, H. Calibration Optimization Methodology for Lithium-Ion Battery Pack Model for Electric Vehicles in Mining Applications. *Energies* **2020**, *13*, 3532. [CrossRef]
78. Doyle, M.; Fuller, T.F.; Newman, J. Modeling of galvanostatic charge and discharge of the lithium/polymer/insertion cell. *J. Electrochem. Soc.* **1993**, *140*, 1526. [CrossRef]
79. Hosseinzadeh, E.; Marco, J.; Jennings, P. Combined electrical and electrochemical-thermal model of parallel connected large format pouch cells. *J. Energy Storage* **2019**, *22*, 194–207. [CrossRef]
80. Smith, K.; Wang, C.Y. Power and thermal characterization of a lithium-ion battery pack for hybrid-electric vehicles. *J. Power Sources* **2006**, *160*, 662–673. [CrossRef]
81. Park, J.; Lee, M.; Kim, G.; Park, S.; Kim, J. Integrated Approach Based on Dual Extended Kalman Filter and Multivariate Autoregressive Model for Predicting Battery Capacity Using Health Indicator and SOC/SOH. *Energies* **2020**, *13*, 2138. [CrossRef]
82. Mao, L.; Xu, J.; Chen, J.; Zhao, J.; Wu, Y.; Yao, F. A LSTM-STW and GS-LM Fusion Method for Lithium-Ion Battery RUL Prediction Based on EEMD. *Energies* **2020**, *13*, 2380. [CrossRef]
83. Dubarry, M.; Svoboda, V.; Hwu, R.; Liaw, B.Y. Capacity and power fading mechanism identification from a commercial cell evaluation. *J. Power Sources* **2007**, *165*, 566–572. [CrossRef]
84. Lei, Z.; Zhang, Y.; Lei, X. Temperature uniformity of a heated lithium-ion battery cell in cold climate. *Appl. Therm. Eng.* **2018**, *129*, 148–154. [CrossRef]
85. Smart, M.C.; Ratnakumar, B.V.; Surampudi, S.; Wang, Y.; Zhang, X.; Greenbaum, S.G.; Hightower, A.; Ahn, C.C.; Fultz, B. Irreversible capacities of graphite in low-temperature electrolytes for lithium-ion batteries. *J. Electrochem. Soc.* **1999**, *146*, 3963. [CrossRef]
86. Shiao, H.C.A.; Chua, D.; Lin, H.P.; Slane, S.; Salomon, M. Low temperature electrolytes for Li-ion PVDF cells. *J. Power Sources* **2000**, *87*, 167–173. [CrossRef]
87. Zhang, S.; Xu, K.; Jow, T. The low temperature performance of Li-ion batteries. *J. Power Sources* **2003**, *115*, 137–140. [CrossRef]
88. Jaguemont, J.; Boulon, L.; Dubé, Y.; Poudrier, D. Low temperature discharge cycle tests for a lithium ion cell. In Proceedings of the 2014 IEEE Vehicle Power and Propulsion Conference (VPPC), Coimbra, Portugal, 27–30 October 2014; IEEE: New York, NY, USA, 2014; pp. 1–6. [CrossRef]
89. Jaguemont, J. Thermal Management of a Lithium-Ion Battery Pack in Winter Conditions including Aging. Ph.D. Thesis, University of Quebec at Trois-Rivières, Trois-Rivières, QC, Canada, 2015.
90. Dong, X.; Guo, Z.; Guo, Z.; Wang, Y.; Xia, Y. Organic batteries operated at −70 °C. *Joule* **2018**, *2*, 902–913. [CrossRef]
91. Piel, T.; Bonenfant, N. How Does Temperature Influence the Autonomy of Lithium-Ion Batteries? Available online: http://tpe-batterie-lithium.e-monsite.com/pages/ii-influence-de-la-temperature.html (accessed on 24 September 2020).
92. EEMB. Lithium-Ion Battery DATA SHEET. Available online: https://www.ineltro.ch/media/downloads/SAAItem/45/459-58/36e3e7f3-2049-4adb-a2a7-79c654d92915.pdf (accessed on 6 February 2022).
93. Ji, Y.; Zhang, Y.; Wang, C.Y. Li-ion cell operation at low temperatures. *J. Electrochem. Soc.* **2013**, *160*, A636. [CrossRef]
94. Herreyre, S.; Huchet, O.; Barusseau, S.; Perton, F.; Bodet, J.; Biensan, P. New Li-ion electrolytes for low temperature applications. *J. Power Sources* **2001**, *97*, 576–580. [CrossRef]
95. Plichta, E.J.; Hendrickson, M.; Thompson, R.; Au, G.; Behl, W.K.; Smart, M.C.; Ratnakumar, B.V.; Surampudi, S. Development of low temperature Li-ion electrolytes for NASA and DoD applications. *J. Power Sources* **2001**, *94*, 160–162. [CrossRef]
96. Zhang, S.; Xu, K.; Jow, T. Low temperature performance of graphite electrode in Li-ion cells. *Electrochim. Acta* **2002**, *48*, 241–246. [CrossRef]
97. Wang, N.; Shang, Y.; Duan, B.; Yu, K.; Wang, T.; Zhang, C. Study on the Effect of Different AC Excitations on the Internal Heating for Low-Temperature Batteries. In Proceedings of the 2019 3rd Conference on Vehicle Control and Intelligence (CVCI), Hefei, China, 21–22 September 2019; IEEE: New York, NY, USA, 2019; pp. 1–5. [CrossRef]
98. Ruan, H.; Jiang, J.; Sun, B.; Su, X.; He, X.; Zhao, K. An optimal internal-heating strategy for lithium-ion batteries at low temperature considering both heating time and lifetime reduction. *Appl. Energy* **2019**, *256*, 113797. [CrossRef]
99. Hoang Huy, V.P.; So, S.; Hur, J. Inorganic Fillers in Composite Gel Polymer Electrolytes for High-Performance Lithium and Non-Lithium Polymer Batteries. *Nanomaterials* **2021**, *11*, 614. [CrossRef]
100. Xing, W.; Sugiyama, H. Improvement in the low temperature performance of gelled polymer lithium-ion cells. *J. Power Sources* **2003**, *117*, 153–159. [CrossRef]
101. Smart, M.C.; Ratnakumar, B.; Behar, A.; Whitcanack, L.; Yu, J.S.; Alamgir, M. Gel polymer electrolyte lithium-ion cells with improved low temperature performance. *J. Power Sources* **2007**, *165*, 535–543. [CrossRef]
102. Smart, M.C.; Ratnakumar, B.; Surampudi, S. Electrolytes for Low-Temperature Lithium Batteries Based on Ternary Mixtures of Aliphatic Carbonates. *J. Electrochem. Soc.* **1999**, *146*, 486. [CrossRef]
103. Smart, M.C.; Ratnakumar, B.V.; Whitcanack, L.D.; Chin, K.B.; Surampudi, S.; Croft, H.; Tice, D.; Staniewicz, R. Improved low-temperature performance of lithium-ion cells with quaternary carbonate-based electrolytes. *J. Power Sources* **2003**, *119*, 349–358. [CrossRef]

104. Smart, M.C.; Ratnakumar, B.; Surampudi, S. Use of organic esters as cosolvents in electrolytes for lithium-ion batteries with improved low temperature performance. *J. Electrochem. Soc.* **2002**, *149*, A361. [CrossRef]
105. Ohta, A.; Koshina, H.; Okuno, H.; Murai, H. Relationship between carbonaceous materials and electrolyte in secondary lithium-ion batteries. *J. Power Sources* **1995**, *54*, 6–10. [CrossRef]
106. Sazhin, S.V.; Khimchenko, M.Y.; Tritenichenko, Y.N.; Lim, H.S. Performance of Li-ion cells with new electrolytes conceived for low-temperature applications. *J. Power Sources* **2000**, *87*, 112–117. [CrossRef]
107. ISTOCK. Installation de Stockage d'Energie par Batterie Constituée de Conteneurs d'Expédition. Available online: https://www.istockphoto.com/photo/battery-energy-storage-facility-made-of-shipping-containers-3d-rendering-gm939827044-256948372 (accessed on 4 February 2022).
108. L'USINENOUVELLE. With Saft, Total Will Install 103 MWh of Batteries in France for RTE. Available online: https://www.usinenouvelle.com/article/avec-saft-total-va-installer-103-mwh-de-batteries-en-france-pour-rte.N939525 (accessed on 12 April 2021).
109. The World of Electricity Online. Total Launches the Largest Battery Electricity Storage Project in France. Available online: https://www.lemondedelelectricite.ca/monde-en-mouvement/4216-total-lance-le-plus-grand-projet-de-stockage-d-electricite-par-batterie-de-france (accessed on 13 April 2021).
110. SAFT. Renewables and Energy Storage: Saft to Build the Largest Energy Storage System in the Nordic Countries. Available online: https://www.saftbatteries.com/fr/m%C3%A9dias-et-ressources/communiqu%C3%A9s-de-presse/saft-construira-le-plus-grand-systeme-stockage-energie-pays-nordiques (accessed on 12 April 2021).
111. TotalEnergies. Renewables and Energy Storage: Saft to Build the Largest Energy Storage System in the Nordic Countries. Available online: https://www.total.com/fr/medias/actualite/communiques/renouvelables-et-stockage-denergie-saft-construira-le-plus-grand-systeme-de-stockage-denergie-des (accessed on 13 April 2021).
112. SAFT. Intensium®Max 20 High Energy (NMC). Available online: https://www.saftbatteries.com/products-solutions/products/intensium%C2%AE-max-20-high-energy (accessed on 13 April 2021).
113. inspire BOX. Energy Storage Containers Become the Norm. Available online: https://inspirebox.fr/les-containers-de-stockage-d-energie-deviennent-la-norme/#:~:text=Les%20syst%C3%A8mes%20de%20stockage%20d\T1\textquoteright%C3%A9nergie%20par%20batterie%20sont%20int%C3%A9gr%C3%A9s,de%20protection%20contre%20l\T1\textquoterightincendie (accessed on 14 April 2021).
114. inspire BOX. A New Containerized Energy Storage System. Available online: https://inspirebox.fr/un-nouveau-systeme-de-stockage-d-energie-en-container/ (accessed on 14 April 2021).
115. Alternative Bike. The Different Types of Batteries and Their Advantages. Available online: https://blog.alternative.bike/conseils/1675-batteries/#:~:text=Batteries%20Nickel%2DM%C3%A9tal%20Hydrure%20(Ni,ph%C3%A9nom%C3%A8ne-%20-d\T1\textquoterightauto%2Dd%C3%A9charge (accessed on 20 April 2021).
116. Schwarz, V. Electrochemical Storage. Available online: https://www.inter-mines.org/global/gene/lin-k.php?doc_id=1012&fg=1 (accessed on 18 August 2021).