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Quantum battery VS Lithium-ion battery

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Abstract. This dissertation aims to research how quantum battery work and the comparisons between quantum battery and lithium-ion battery. Lithium-ion batteries are rechargeable energy storage devices that have become widely used in various applications, ranging from portable electronics to electric vehicles. They are known for their high energy density, long cycle life, and relatively low self-discharge rate. Quantum batteries are a relatively new and emerging concept in the field of energy storage. Unlike traditional batteries, which rely on chemical reactions for energy storage, quantum batteries utilize principles from quantum physics to store and release energy. The dissertation uses the available literature review to illustrate the difference between quantum batteries and lithium-ion batteries for storing energy, and which one is better. In terms of current technology, lithium-ion batteries are the best choice for portable charging devices. But in the future, quantum batteries made with advanced technology may replace lithium-ion batteries.

Keywords: quantum battery, lithium-ion battery, batteries

1. Introduction

The escalating population in developing nations has led to a commensurate increase in power consumption. Global electricity consumption has consistently grown over the past centuries, reaching approximately 25500 terawatt-hours in 2022 [1]. Fossil fuels continue to dominate as the primary source for power generation, accounting for 82% of energy consumption in 2022, marking a 1% increase from 2021 [51]. Consequently, carbon emissions reached a record level of 417.2 parts per million in comparison to the previous year's value of 416 parts per million [2]. The mounting emission of greenhouse gases into the atmosphere from fossil fuel combustion is causing devastating consequences worldwide including climate change and global warming [3], resulting in natural disasters and extreme weather events such as flash floods and droughts. Decarbonization plays an indispensable role in achieving net zero by2050. Net Zero aims to strike an equilibrium between greenhouse gas emissions and removal [4]. This can be accomplished by transitioning towards more sustainable energy solutions that reduce the reliance on fossil fuels while minimizing CO_2 and other greenhouse gas emissions into the atmosphere [5]. However, current energy storage technologies like fixed batteries and fuel cells constrain the ability to efficiently store renewable energy.

As combating climate change effects, quantum batteries hold promise as sustainable energy storage solutions. By harnessing entanglement and super-absorption through quantum mechanisms, these batteries could offer reliable means of storing energy while mitigating climate change impacts.

Quantum batteries consist of quantum mechanical systems where electromagnetic fields or qubits store energy [6]. In modern society, the use of quantum batteries for widespread energy storage of renewable energy could reduce the time and economic costs compared to traditional energy storage materials [56].

Quantum batteries could also reduce heat energy wasted in traditional power supply, thus contributing to decarbonization effects, and preventing the destruction of the atmosphere. Lithium- ion batteries were first commercialized in 1991, over the past decades, it has been considered the most efficient energy storage system due to high energy density, power density, and stability. As a result, the lithium-ion battery has been widely applied in portable devices, such as powering electric vehicles. However, as the demand for advanced energy storage is increasing continuously, the lithium-ion battery cannot satisfy the market needs even if it has the highest energy density of present systems. Therefore, it is desirable to innovate advanced materials or batteries for higher energy density.

This paper will attempt to identify the current progress of quantum battery development and describe and explain the applications of quantum batteries. The operating characteristics of quantum batteries will be illustrated. Furthermore, there will be an analysis of existing lithium-based batteries compared to quantum batteries. Finally, the feasibility of quantum batteries in future societies will be evaluated and their long-term effect on environmental protection will be discussed.

2. Literature review

2.1. Battery

Battery is a device that converts chemical energy into electrical energy directly. The redox reaction between the electrolyte and the metal is the working principle of a battery. Place two distinct metal substances in a diluted electrolyte and allow them to undergo oxidation and reduction reactions on the electrode, which are determined by the reduction potential of the metal. The tendency of an electrode to acquire electrons is referred to as its reduction potential [27]. As a result of the oxidation reaction, anode becomes negatively charged and is designated as the cathode, whereas the reduction reaction results in the other electrode being positively charged and designated as the anode [9]. Batteries have a multitude of applications in various medical devices.

Prosthetics, insulin pumps, hearing aids, and valve assist devices are all devices that run on batteries. The electrocardiogram monitor is connected to the battery, allowing it to move with the patient and remain continuously operational to display their vital signs [27].

Rechargeable batteries can perform 500 to 1200 cycles of charging and discharging before their capacity drops to 80% of the initial value. When their battery capacity drops below 80%, the charging and discharging cycles are significantly reduced [10]. Battery recycling typically involves smelting, which typically leads to the loss of metal ions and other raw materials. The new hydrometallurgical process utilizes dissolution to separate battery metal from waste, capable of recovering all metals; however, it does so at the expense of consuming a significant amount of energy and chemicals, and frequently results in the production of contaminated wastewater [11].

To avoid and improve the drawbacks of traditional batteries, many applications nowadays use lithium-ion batteries to replace traditional lead-acid or nickel-based batteries. The combination of high energy density, rechargeability, long cycle life, and other favorable characteristics has made lithium-ion batteries the preferred choice for numerous industries and consumers alike.

2.2. Lithium-ion battery

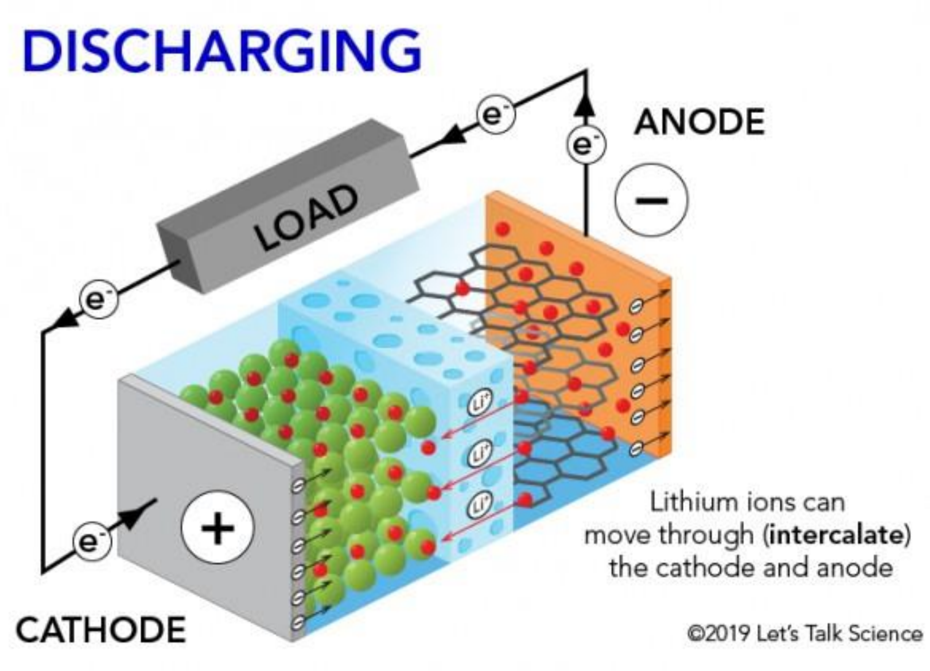

Figure 1. The orange part is the anode (positive side) of the lithium battery. The grey material is cathode (graphite negative side) of the lithium battery. The blue material in the middle is porous separator. Beside the separator, the green stuff is lithium metal oxide, and the red dot is lithium-ion. Source: https://letstalkscience.ca/educational-resources/stem-explained/how-does-a-lithium-ion- battery-work

Lithium-ion battery was commercialized since 1973 for rechargeable solar calculators and has since been widely used in electronic devices. Lithium-ion battery is made up of graphite anode, Lithium Cobalt Oxide, $LiCoO_2$ cathode, lithium salt electrolyte, a separator, and positive and negative collector. The anode and cathode are used to store the lithium. The movement of lithium ion from the lithium-cobalt oxide, anode side creates electrons and gives up some lithium ions move through the electrolyte to graphite electrode to charge the positive collector, while the battery discharges, the electrons come to the opposite directions, the lithium ions move back from the negative side to anode [12]. Electrons do not flow through the electrolyte since it is an insulating barrier. The electrons flow through the external circuit to create a voltage. Inside the lithium-ion battery, a redox reaction occurs during charging and discharging. Lithium is a low-density metal which alleviates the mass of battery, and its large standard electrode potential of -3.4V allows it to operate at high voltages. Lithium-ion battery is widely applied in automotive application by packaging thousands of individual lithium cells together [13]. Therefore, the capacity of a lithium-ion car battery is about 40 kWh to 200 kWh [14]. For example, if a battery of Tesla is fully charged, it can travel about 320-340 miles. For mobile phones, the battery retains to undergo 850 charge and discharge cycles before declining to 80%. After two to three years of use, the battery is only 80% of its original charge, and then the rate of consumption will be even faster [15].

The energy that the battery can deliver during discharging is called capacity. The capacity of lithium-ion battery can be measured in milliampere-hours, for example, a 1000 mAh li-ion battery can work for 1000 hours with 1 mA current. The capacity depends on the number and size of lithium cells, and the density of electrolyte. A larger number and size of cell enhances the ability of Li-ion battery to store or transfer energy. Adding a high-density electrolyte is another way to enhance its capacity, but this shortens the battery life [16]. With each charging cycle, the capacity and power of Li-ion battery decreases, eventually reaching the end-of-life point when capacity decays by 20%. Overheating, overcharging and short circuit will occur if the critical point is exceeded. Lithium-ion battery has the highest energy density among all commercial batteries of about 300 Wh/kg, 4 times larger than the any other battery. Furthermore, it can offer 3.6 voltage, 1.5 to 3 times of the alternatives [17].

2.3. Quantum battery

Quantum mechanics studies the basic theory of the structure and properties of atoms, molecules, condensed matter, atomic nuclei, and elementary particles [18]. Qubits utilize the superposition phenomenon of quantum mechanics to achieve linear combinations of two states. Classical binary bits can only represent a single binary value, either 0 or 1, implying that they can only be in one of two possible states. In contrast, qubits can represent 0, 1, or any ratio of 0 to 1 in the superposition of these two states, with a certain probability of 0 and a certain probability of 1 [19]. Quantum batteries consist of a quantum system that can store energy utilizing the quantum mechanics of photons entanglement. Quantum batteries are developed based on super-absorption too. Entanglement facilitates photon trapping in molecules, since molecules are inherently linked to each other independent of their physical distances and is the main element in charging quantum batteries [20]. And when the nano-structured solid state of matter in which electrons absorb photons become stable, particles can hold and retain energy in the battery for indefinite time (Bart 2022). Super-absorption refers to the enhanced rate of light absorption as the number of molecules increases [21]. Hence, the efficiency of a collective quantum mechanical system in the battery is much higher compared to individual systems [22]. As figure 2 shows, increasing the number of entangled copies increases the amount of energy that can be extracted from each battery. When utilizing a machine that operates in a reversible cycle, optimal amount of energy can be extracted from a single copy of quantum state [23].

With the advent of quantum computing and communication, there has been an increasing amount of research on quantum batteries within the last decade.

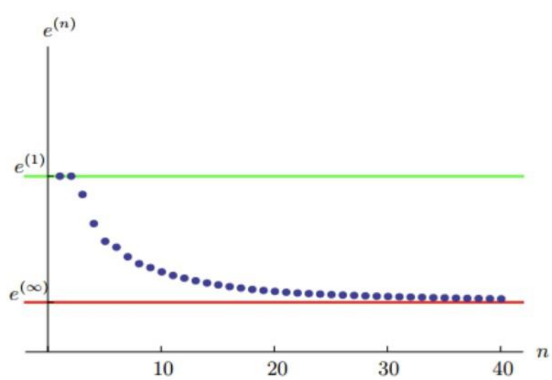

Figure 2. The x-axis labelled n Represents the number of qubits in a quantum battery, the y-axis e represents the energy that can be extracted from each qubit. The graph shows that as the number of the entangled copies increases, the total amount of energy from the battery increases. Source: https://www.extremetech.com/extreme/139857-quantum-entangled-batteries-could-be-the-perfect- power-source

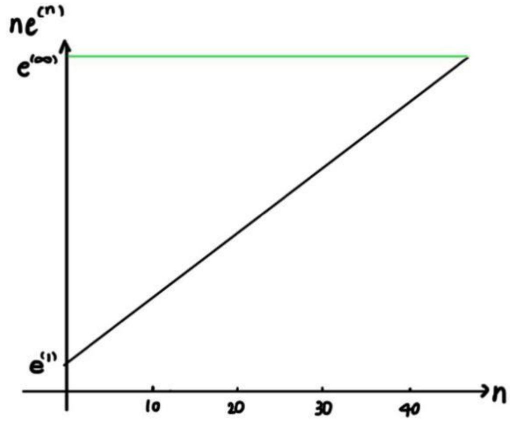

Figure 3. the figure shows total energy(nen) vs. n.

The structure of a quantum battery is shown in figure 4.

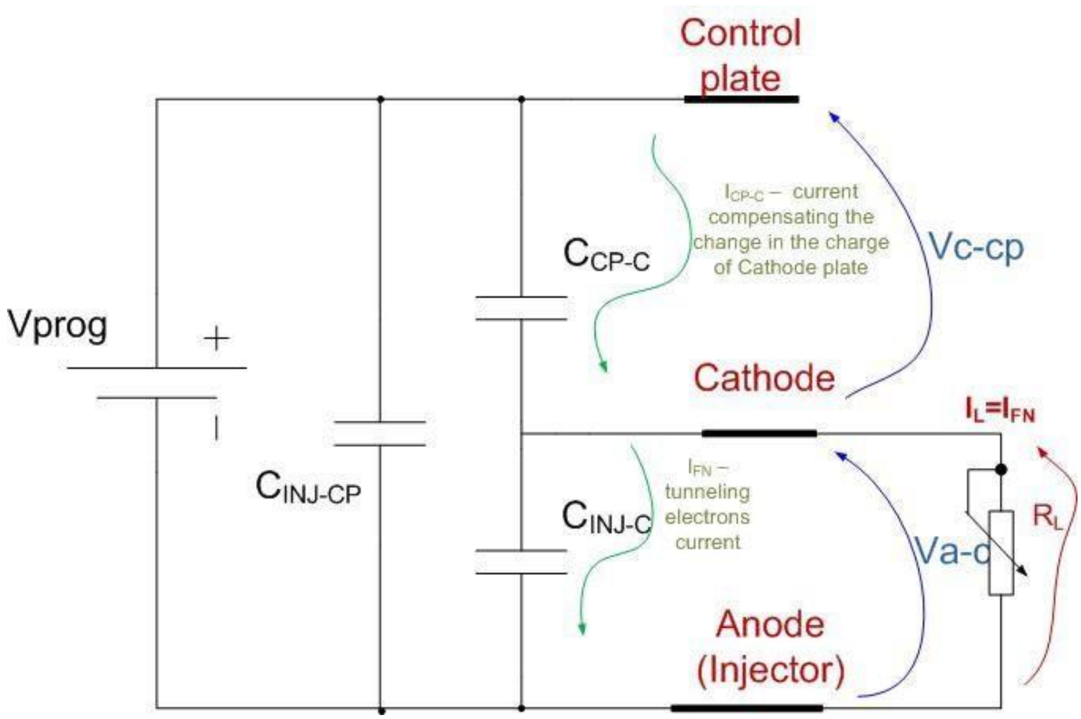

Figure 4. Structure of a quantum battery consisting of components. *C* labels the capacitors, *Vprog* is the voltage from the 'control plate' the tunneling current will start to flow. **C***CP-C* – the capacitor between the Control plate and the Cathode. *C*INJ-C – the capacitor between the Anode and the Cathode. **C***INJ-CP* – the capacitor between the Anode (Injector) and the Control plate. Source: https://www.instructables.com/Quantum-battery/

In a coherent state, transition amplitudes of dye molecules of electrons exhibit wave-like interference; When they constructively interference, the resultant amplitude of the entire system will be greater than the sum of its individual parts. The interference results in the battery charging faster compared to traditional parallel devices. The charging speed is even more impressive as it is 'super scalable', implying that as more and more dye molecules - storage units - are incorporated into the battery, the charging speed will enhance, about 200 times. [24]. For example, quantum battery can shorten the charging time of electric car from 10 hours to 3 minutes.

Quantum battery consists of 3 conducting and 2 insulating layers. The bottommost layer is anode, the positive pole of the battery. The layer above it is called cathode, which is the negative pole of the battery. They are isolated by a thin dielectric layer, creating a capacitor to store electrons and electrical energy [25]. Same to the right plate, for Ccp and CINJ-C, the total number of charges cancels and becomes electrical neutral. If no voltage is applied in the electric field, the Ccp capacitor does not store the electric charge. Inside the capacitor, the two plates are made up of aluminum, which are connected by terminals and separated by dielectric [26]. When the capacitor connects with a power source, both conductors are accumulating the electric charges, one receives the positive charges and the other one receives negative charges. The plates are electrical conductors, they can pass the electric current easily through them and store electric charge.

Dielectric material is a non-conducting and non-metallic substance that holds electrical charges.

The distance between two layers is about few nanometers. The empty space between two layers is filled with non-conductive material or insulator, such as air, vacuum, glass [25]. If the dielectric is in the electric field, the electric charges won't flow through the material, however, if the electric charges shift slowly from the equilibrium position in the field, causing dielectric polarization. Dielectric polarization causes the positive electric charges flow in the direction of the field, and the negative charges flow in the opposite direction, producing an internal electric field which reduces the overall electric field of the dielectric material. [27].

Capacitors are used to maintain the voltage at a certain level. When applying high voltage to the parallel circuit, the capacitor is charged, otherwise, it is discharged with low voltage applied.

Although the electricity flows out in alternative current, most circuits need to work with direct current. Therefore, the alternative current converts into direct current by a rectifier circuit. However, the converted direct current is not a stable current that includes ripples. The function of capacitor is to delete the ripples and maintain the overall voltage within the circuits [28]. Modern physics believes that quantum tunneling is the main mechanism by which stars radiate light.

Photons are generated from within the core of a star tunnel to its periphery, which can be released as free energy in space. An example is EEPROM, which is used as a memory in almost every electronic device. EEPROM chips contain millions/billions of special electronic devices called floating gate MOS transistors (FGMOS), which operate based on electron tunneling. When Vprog is applied, the tunneling current IFN begins to flow. As time progresses, the absolute value of the negative potential Va-c of the cathode plate charged by it increases. The voltage on Ccp-c also varies over time, causing the current Icp-c to flow out from the Vprog source. When the voltage Va- c reaches a predetermined level, an adjustable resistive load can be connected between the cathode and anode. The resistance RL of the load can be adjusted to ensure that the load current IL=Va- c/RL matches IFN. Then, the charge on capacitor CINJ remains constant, along with the value of Va-C. This implies that the stored charge in capacitor CCP-C: Q (CCP-C) also remains constant, as the voltage VC-CP remains constant. The power supply will not consume any energy, however, the energy in the load will be dissipated [29].

3. Discussion and development

This dissertation will develop from the applications, environmental impact, and social levels of the comparison between lithium-ion batteries and quantum batteries.

3.1. Applications EVs

The term Lithium-Ion battery was first coined back in 1912, by G.N Lewis. In the 1970s, the first non-rechargeable lithium battery was commercialized and introduced into the market. Until 1991, Sony invented the first rechargeable lithium battery [30]. Lithium-ion batteries provide electricity through the movement of lithium ions. Lithium ions come from lithium metal oxides and lithium cobalt oxides. When a lithium-ion battery is powered, the positively charged lithium ions move through the electrolyte, moving from the negative electrode to the positive electrode. When charging, lithium ions return from the cathode to the anode, and electrons move from the anode to the cathode [31]. Lithium-ion batteries have various applications, such as digital cameras. Rechargeable lithium-ion battery packs are smaller in size and have higher power and capacity than other types of batteries. In addition, lithium-ion batteries are also used to store solar energy. The main reason is that its charging method matches the solar panel, and the low resistance generated by the solar panel can accelerate the charging of lithium batteries [32].

In the transportation sector, lithium-ion batteries have revolutionized the electric vehicle (EV) industry, as the key component of device that store renewable energy. Lithium-ion batteries have a high energy density, meaning they can store a large amount of energy in a relatively small and lightweight package. Since it first commercialized in 1991, the energy density of it has risen from 80 Wh/kg to about 300 Wh/kg [33]. As figure 4 illustrates the energy density of lithium- ion batteries rose dramatically between 2008 and 2020, as figure for from 55Wh/L to 450Wh/L. The electrodes for lithium batteries are made of lightweight lithium and carbon. Because of lithium's high activity, its atomic bonds can store a lot of energy. A lithium-ion battery can store 150 watt-hours of electricity in a kilogram of batteries, compared with 6 kilograms for a lead-acid battery to store the energy that a kilogram of lithium-ion batteries can handle [34]. High density battery can deliver same amount of energy but in smaller space compared to low density battery.

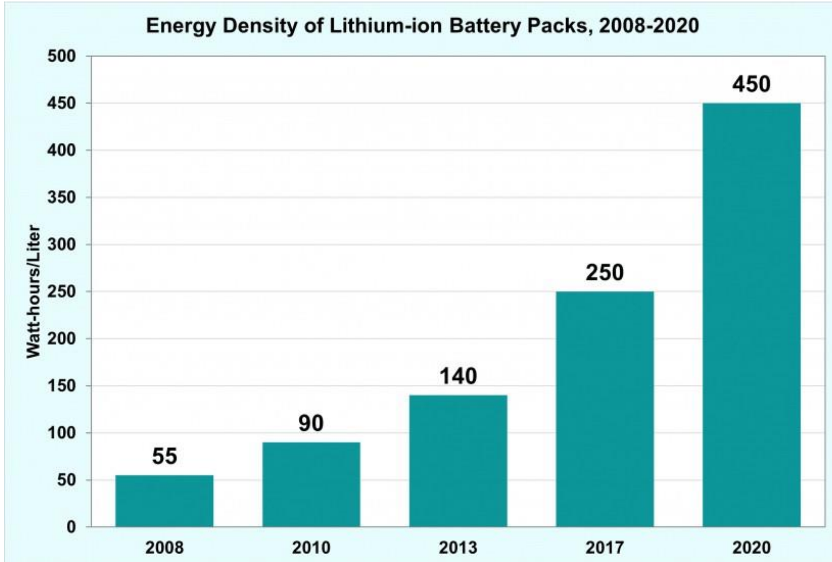

Figure 5. the figure illustrates the upward trend of the energy density of lithium-ion battery. Source: https://www.energy.gov/eere/vehicles/articles/fotw-1234-april-18-2022-volumetric-energy- density-lithium-ion-batteries

Managing the temperature of a lithium-ion battery is critical for its performance and longevity. EVs often include sophisticated thermal management systems to keep the battery within an optimal temperature range, preventing overheating and ensuring efficient operation. Lower temperatures reduce the battery's output, thereby decreasing its range and available power. Even when an electric vehicle is not in use, its thermal management system continuously monitors and maintains the internal temperature within this range. Although any temperature outside of the optimal comfort zone can affect the efficiency of electric vehicles, these vehicles are equipped with intelligent systems to maintain their systems within their comfort zone. Every battery operates optimally within a specific temperature range. In the case of lithium-ion batteries, this temperature range typically falls between -20℃ and 60℃ [35]. Lithium-ion batteries operate optimally within the temperature range of 15-45°C during discharging. Batteries prefer to remain below 45°C, while during rapid charging, they prefer a slightly higher temperature, around 55°C, to minimize the battery's internal impedance and allow electrons to quickly charge the battery. Exceeding this temperature can cause damage to the cells, thus temperature management involves a balancing act.

Overheating can harm lithium-ion batteries. When the temperature surpasses 45℃, the electric vehicle battery deteriorates swiftly, necessitating control by a heat exchanger. As batteries charge or discharge, they generate internal heat. Most of this heat moves through a metal collector and is extracted in the busbar, either through convection or conduction from the battery to the cooling plate to the coolant through the cold plate beneath the battery. It then leaves the battery pack and is expelled through an external heat exchanger. If the battery charges too quickly and its internal temperature surpasses approximately 70℃, the system must swiftly act to immediately reduce the battery temperature, lest thermal degradation of the battery initiates a thermal runaway process.

When the battery overheats, heat triggers an exothermic chain reaction within the battery, generating gas. If this gas is ignited, it can lead to an internal fire in the battery pack. In colder climates, the thermal management system of electric vehicle battery systems generates heat to maintain the temperature above the minimum threshold. They warm the battery before use. At colder temperatures, the internal dynamics of the battery lead to lower charging and discharging rates, reducing the available battery power. Low temperatures can hinder the chemical and physical processes that contribute to the efficient operation of electric vehicle batteries [36]. If left unchecked, this can lead to increased charging times and reduced range. In extreme cold conditions, injecting an excessive charge into the battery can cause lithium to form dendrites, which can pierce the separator between the anode and cathode, leading to an internal short circuit in the battery. Thus, in extremely cold climates, it is essential to regulate the charging rate to carefully warm the battery, and only increase the charging rate once the battery rises above the minimum operating temperature. The self-discharge rate of lithium-ion batteries increases with increasing temperature. This means that the battery will lose power faster when not in use, leading to a shortened standby time [37].

For a certain number of lithium-ion batteries in a prescribed environment in a period time, the phenomenon of rate of capacity self-depletion is called self-discharge. Lithium-ion batteries have a low self-discharge rate, meaning they lose charge at a slower rate when not in use. Battery self- discharge is an internal chemical reaction. This allows devices powered by lithium-ion batteries to retain their charge for longer periods, making them more reliable and convenient [38]. However, lithium-ion batteries have a distinct advantage in terms of self-discharge compared to other battery types. Nickel-based batteries have the highest rate of self-discharge, accounting at 20% per month. On the other hand, lithium batteries have the lowest self-discharge rate, as low as 3.5% per month [39]. The use of high-quality materials and advanced manufacturing techniques contributes to reducing self-discharge in lithium-ion batteries. The electrodes are typically made of materials with high stability, such as $LiFePO_4$ or $LiCoO_2$. These materials exhibit minimal side reactions, resulting in lower self-discharge rates.

There is a counter-intuitive property of quantum battery which is the recharge time is inversely related to the capacity (Figure 2.1), is also the amount of storage of charging. The speed of charging power increases when the size increases. Quantum batteries can be collectively charged through quantum entanglement or coherence in quantum phenomena. The collective charging protocol creates entanglement between batteries to couple different systems. In the quantum case, the wave function of the system overlaps with the higher energy eigenstates, and the charging speed depends on the rate of diffusion of the wave function. If the batteries are entangled, the charging speed, called variance, increases with the number of battery packs [40]. In quantum battery, the power increases with the square of the number of cells. The maximum charging speed of a conventional battery increases linearly with the number of cell cells, while quantum battery uses global operation to achieve a binary system of the charging speed. For example, a typical electric car battery contains about 200 cells and is charged using quantum batteries, which are nearly 200 times faster than conventional batteries, meaning that the tram's charging time is reduced from ten hours to three minutes [6]. If quantum battery replaces lithium-ion battery to work as the motivation of electric vehicles in the future, the charging time will deduct significantly.

3.2. Quantum sensors

Quantum mechanics attempts to describe the properties of molecules and atoms and other particles such as quarks and gluons [41]. Quantum battery is a quantum mechanical system that stores energy of photons. A photon is a quantum of light and a carrier of the electromagnetic force. Photon displays properties of both particles and waves [42]. Quantum battery could store energy in the excited state and charge very fast because of entanglement and super absorption. Entanglement is a phenomenon that explains how two subatomic particles connect to each other even they are separated by billions of light-years of space. By entangling many quantum batteries together can enhance the output of each battery [43]. When each molecular dye of the quantum unit is placed in a coherent state, the amplitude of the transition of the dye will interfere with each other like a wave. They produce peaks when they produce constructive interference and troughs when they produce destructive infections. Even if the parts of the quantum battery do not act, under constructive interference, the transition amplitude of the entire system is greater than the sum of the parts [44]. The quantum world is probabilistic, which applies to quantum batteries and quantum computing. When an energy storage unit presents an excited or ground state in the traditional world, it will behave as a superposition of the two in the quantum world [44]. The environment plays a vital role in charging quantum battery, if there is a coupling exists between environment and battery, then the quantum battery can be charged properly.

While the most advanced applications of quantum computing and the quantum internet remain a long-term venture, prototypes and products have already emerged in other areas of quantum technology. An atomic clock serves as an illustration. Initially developed to offer more precise timing, the research community is now refining atomic clocks, making them more sophisticated, tailored for applications such as high-speed mobile communication, synchronized financial transactions, and other instances where precise and flexible timing can confer commercial benefits. The application of quantum sensors is continually evolving. An example is the gravity sensor developed by Muquans, a pioneering French company in quantum sensing. The gravity sensor is conceptually rooted in Newton's free-fall experiment, and technically employs a rubidium atomic cloud cooled to near absolute zero as the test mass [45].

Quantum batteries could be utilized in highly sensitive quantum sensors, contributing to advancements in fields such as precision measurement and quantum metrology. Quantum sensing, an advanced sensor technology, significantly enhances the precision of measurements, navigation, research, exploration, observation, and interaction with the world by detecting changes in motion, electric, and magnetic fields [46]. Quantum sensing employs the fundamental principles and phenomena of quantum mechanics to precisely measure physical parameters. In general, there are three primary methods for quantum sensing: (I) utilizing quantum objects to measure physical parameters. (II) employing quantum coherence to measure physical parameters.

(III) leveraging quantum entanglement to enhance measurement sensitivity or accuracy beyond classical limits [47]. Quantum sensors can record even the tiniest signals and changes and measure them with greater precision than any sensor previously produced, whether it's magnetic field, acceleration, or pressure. Unlike traditional sensors, the measurements made by quantum sensors usually correspond directly to the physical dimension reference values of SI units. This eliminates the need for calibration, as it would otherwise be necessary, thereby saving costs [48].

On the other hand, quantum battery also must tackle to the problem of temperature. Entanglement can very easily be broken down by the environment. If entanglement is maintained at low temperatures and intermediate coupling strengths, multiple entanglements may form between qubits and between high spins [49]. Quantum coherence is more stable at room temperature, but it is also easily disrupted. Entanglement does not grow to its maximum value, but rather to its maximum value within the constraints of energy conservation in the initial state, likely at a finite temperature. Indeed, at low temperatures, the later state of the system will locally resemble the ground state, which has weak entanglement with non-critical local Hamiltonians. Thus, to observe a notable expansion of entanglement, typically encounter it at high energies/temperatures, much like the entropy of a thermodynamic system [50].

3.3. Environmental impact

The production of lithium-ion batteries, which power electric vehicles, emits more carbon dioxide than the production of gasoline-powered vehicles. Approximately 40% of the climate impact from battery production originates from the extraction and processing of essential minerals. The extraction and refining of battery materials, along with the manufacturing of batteries, modules, and battery packs, consume substantial amounts of energy and contribute to greenhouse gas emissions. China holds a dominant position in the global electric vehicle battery supply chain, with nearly 60% of electricity sourced from coal, a greenhouse gas-intensive fuel. Compared to conventional batteries, the cumulative energy requirement for producing lithium-ion batteries is three times that of regular batteries. If the battery is eventually disposed of in a landfill, its components, including heavy metals, may leach into the soil and groundwater. Landfilling lithium-ion batteries heightens the risk of fire. Due to its distinct chemical composition and structure, batteries pose challenges for efficient recycling [51].

Over time, the performance of batteries may decline, but discarded batteries can still provide useful energy storage for other applications. For instance, if an electric vehicle battery's energy cannot meet the owner's range requirements, it can be repurposed as an electric vehicle battery for customers with lower range requirements, or it can be transformed into a new battery to store the energy generated by solar panels. The options for reuse and repurposing are still under development, but one day they may provide a "second life" for batteries on a larger scale before recycling. This second lifespan will benefit the environment by extending the lifespan of batteries and reducing the resource demand for manufacturing new batteries, thereby reducing pollution and harmful substance emissions [52].

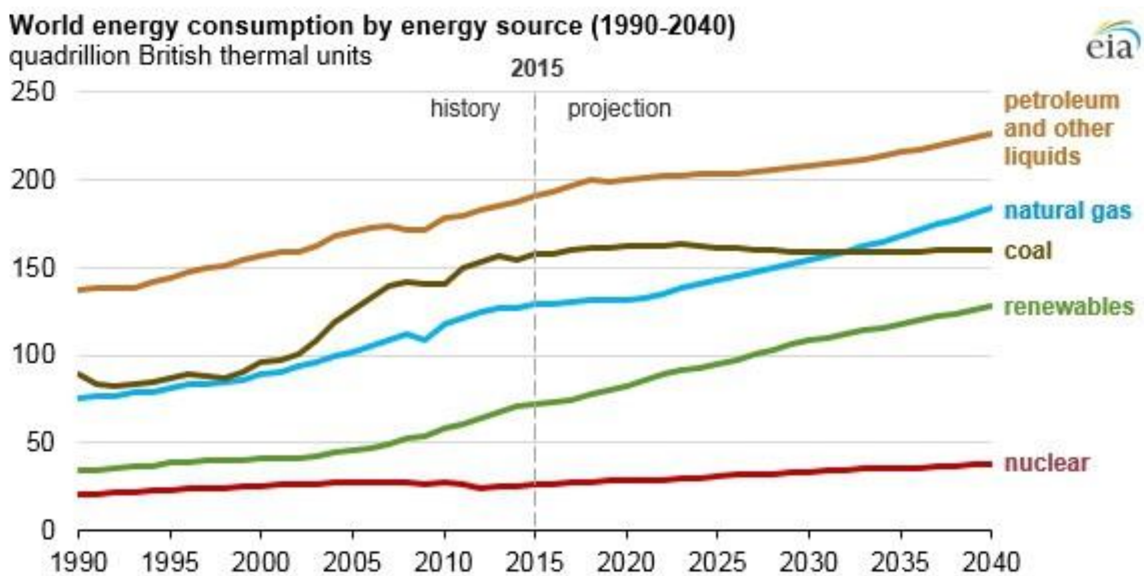

Figure 6. world energy consumption from 1990 to 2040
Source: https://www.eia.gov/todayinenergy/detail.php?id=32912

Statistics show that by 2040, the level of global energy consumption is expected to increase by 28% compared to 2015. Although a significant share of energy still comes from fossil fuels, this carries a huge environmental cost. Driven by quantum mechanics, quantum batteries are expected to be applied to new energy vehicles, organic photovoltaic devices, light detectors, energy collection technology and other fields involving energy conversion and innovation [53]. One immediate application is the use of quantum batteries in quantum devices such as quantum computers to provide quantum energy sources for quantum computers. Quantum batteries are expected to be used in applications requiring high power charging and discharging, such as military equipment, emergency response devices, etc., which can greatly shorten the time required for energy transfer and speed up the response speed.

Quantum batteries have the potential to be more environmentally friendly compared to traditional batteries. Conventional batteries often rely on rare and toxic materials, such as lithium and cobalt, which can have detrimental environmental impacts during mining and disposal. Quantum batteries, on the other hand, can be designed using more sustainable materials and manufacturing processes, reducing their ecological footprint, but the specific materials that would be used in such a device are still unknown and subject to ongoing research and exploration.

3.4. Social level

China currently dominates the global lithium-ion battery supply chain, producing 79% of the available lithium-ion batteries in the global market in 2021. In addition to China, European countries are also increasing the production of lithium-ion batteries. It is speculated that by 2025, the EU is likely to become the world's second largest producer of lithium-ion batteries, accounting for 11% of global production capacity. Starting from 2021, the cost of lithium-ion batteries has continued to rise to over 900% of the original level. Coupled with inflation, the prices of equipment using lithium-ion batteries as raw materials are also rising, such as electric cars [54].

The industrialization of quantum batteries has the potential to impact various aspects of energy storage technology, including lithium-ion batteries. Quantum batteries, which utilize quantum properties to store and release energy, offer the possibility of higher energy densities and faster charging times compared to traditional lithium-ion batteries. However, quantum batteries do not have a clear prospect of being commercial batteries. Conventional batteries do not require the same rigorous environmental conditions to induce strong or weak coupling environments as quantum batteries [55]. As far as the research of quantum battery systems is concerned, the physical systems (materials) that meet the conditions, the technology to accurately manipulate these systems, the method of designing quantum batteries with optimal performance, and the method of extracting and using energy from quantum batteries need to be solved one by one. Linking quantum battery as a collective system reduces the amount of energy wasted and allows a faster charging time, the overabsorption effect of quantum batteries is based on the properties of quantum superposition. As the size of the microcavity and the number of molecules increase, the charging time of the quantum battery decreases [56]. Therefore, holding enormous potential in realizing decarbonization and net zero in the future. By reducing energy wasted as heat, quantum batteries eliminate the need for an extensive cooling system powered by fossil fuels in traditional national grid supply. Additionally, lithium-ion batteries have already established a strong presence in various industries and applications, and they continue to undergo advancements in terms of energy density, safety, and cost-effectiveness. Therefore, while the industrialization of quantum batteries may have an impact on the future of energy storage, it is difficult to predict the extent of its influence on lithium-ion batteries specifically. Continued research and development in both quantum batteries and lithium-ion batteries will shape the future landscape of energy storage technologie

4. Conclusion

In answering the comparisons between lithium-ion battery and quantum battery, also how quantum battery works. This dissertation has explored various theories and phenomenon from the structures and principles of the two types of batteries. By making comparisons from different aspects like lifespan, power, efficiency and so on, in these aspects, quantum batteries are superior to lithium-ion batteries, but because quantum batteries are still in development and their future implementation is currently uncertain, they are only practically inferior.

Lithium-ion batteries work as a major role in daily life. For electric vehicles, the high energy density of lithium-ion battery is crucial, where minimizing weight is essential for efficiency and range. At the same time, low self-discharge rate ensures the discharging time and longevity of a device at optimum temperature. If the temperature is too low or too high, lithium-ion batteries will shorten the lifespan and lose power.

Quantum batteries represent a potential advancement in energy storage technology within the wider field of battery research and development. They utilize quantum properties, such as superposition and entanglement, to store and release energy. While still in the early stages of development, quantum batteries have the potential to offer higher energy densities and faster charging times compared to traditional batteries. However, they have the same drawbacks as lithium-ion batteries- temperature controlling. The development of quantum batteries requires significant investment in research and development. The emergence of quantum batteries could disrupt the existing battery market, including lithium-ion batteries.

There could be further research done on the prospects of quantum batteries to apply in industrialization. Because currently, due to technological and environmental challenges, quantum batteries have not been implemented in industry. It is uncertain how it will impact daily life in the future. Improvements of lithium-ion batteries can be also researched further to meet increasing demands, especially since they play countless important roles in human daily activities, ranging from transportation vehicles to telecommunications companies, household appliances, and portable devices.

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