Introduction of Battery Research: General Overview and What to Look

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Abstract

This mini paper provides an introduction to battery research, offering a comprehensive overview of the subject matter and highlighting key areas of interest. The paper begins with a brief history of battery invention, exploring the development of batteries and the notable individuals behind their creation. A clear definition of batteries is presented, followed by an exploration of different battery types and their specific requirements. The paper also delves into the global battery market, discussing various battery types and advancements in the field. It further examines the challenges and prospects associated with the advancement of battery technology. This mini paper serves as a foundation for understanding the broader landscape of battery research, setting the stage for further exploration in this dynamic and evolving field.

Contents

1 Introduction

Batteries are essential energy storage devices that play a crucial role in our modern society. From powering portable electronics to electric vehicles and renewable energy systems, batteries have become an integral part of our daily lives. This paper aims to provide a comprehensive introduction to battery research, offering a general overview of the subject and highlighting key areas of interest.

The paper begins with a brief exploration of the short history of battery invention, delving into the development of batteries over time and acknowledging the significant contributions of inventors in shaping this technology. Understanding the historical context is vital for appreciating the progress and advancements achieved in battery research.

Next, the paper defines what a battery is and examines the different types of batteries available in the market today. This section provides a framework for understanding the various battery chemistries and their unique characteristics. Additionally, it highlights the requirements that batteries must meet to be considered viable energy storage solutions.

The global battery market and recent advancements in battery technology are discussed to shed light on the current state of the industry. This section provides an overview of the different battery types dominating the market and explores the latest innovations and breakthroughs that have propelled battery technology forward. Furthermore, it addresses the challenges faced by researchers and the prospects for future advancements in battery technology.

By presenting this comprehensive overview, this research paper aims to equip readers with a foundational understanding of battery research. As battery technology continues to evolve rapidly, staying informed about the latest developments and understanding the broader context becomes crucial for researchers, industry professionals, and anyone interested in the world of batteries. It acknowledges the contributions of Battery University's "Crash Course on Batteries" as a primary source of information while incorporating insights from other reputable references [1]. It also acknowledges the contribution of electrochemistry paper from Andra Oktafian as a good starting point before researching battery technology [2].

2 Short History of Battery Invention

2.1 Battery Development

The discovery and practical use of electricity have revolutionized human civilization. While its widespread application began in the mid to late 1800s, there is evidence suggesting the use of electricity may date back even further. The Parthian Battery, believed to be 2,000 years old, was discovered in Baghdad and consisted of a clay jar filled with a vinegar solution, an iron rod, and a copper cylinder, producing a small amount of electricity. However, its purpose and function are still debated among scientists. Figure 1 illustrates the Parthian Battery.

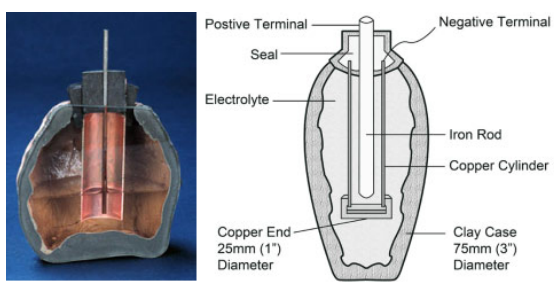


Figure 1: **Parthian Battery**. A clay jar of a prehistoric battery holds an iron rod surrounded by a copper cylinder. When filled with vinegar or electrolytic solution, the jar produces 1.1 to 2 volts.

Early advancements in generating electricity included static charge experiments by Otto von Guericke in 1660 and the development of the Leyden jar by Ewald Georg von Kleist in 1744. Alessandro Volta's invention of the voltaic cell, or battery, in 1800 marked a significant milestone in the continuous production of electrical power. Luigi Galvani's discovery of animal electricity and Volta's subsequent experiments led to the widespread interest in galvanic electricity.

The invention of the rechargeable battery began with John F. Daniell's improved battery in 1836, followed by Gaston Planté's lead-acid battery in 1859, which was the first rechargeable battery. Subsequent developments included the nickel-cadmium (NiCd) battery in 1899 and the nickel-iron (NiFe) battery in 1901. NiCd batteries faced environmental concerns, leading to the development of the more eco-friendly nickel-metal-hydride (NiMH) battery. The focus of current research is primarily on improving lithium-ion (Li-ion) batteries due to their high energy density, simple charging, and environmental advantages.

The understanding of magnetism's relationship to electricity led to the invention of electric generators and motors in the early 19th century. Michael Faraday's experiments demonstrated the generation of electricity through magnetic fields, leading to the development of electric generators and motors. The introduction of transformers enabled the conversion of alternating current (AC) to different voltages, facilitating the transmission of electricity over long distances.

The disagreement between direct current (DC) and alternating current (AC) systems was resolved in favor of AC, thanks to Nikola Tesla's contributions. Tesla's AC transmission system, supported by George Westinghouse, enabled the transmission of electricity over long distances and became the accepted norm for power distribution.

The development of telegraphy and the invention of the vacuum tube in the early 20th century further advanced the use of electricity. It led to significant breakthroughs such as radio broadcasting, the first digital computer (ENIAC), the invention of the transistor, and the arrival of integrated circuits and microprocessors, shaping the Information Age and transforming the way we live and work.

Today, electricity has become an essential part of modern life, and portable power sources like batteries play a crucial role in meeting the increasing demand for mobility and powering various devices and technologies. Ongoing advancements in battery technology continue to expand the possibilities of portable power and its applications in various fields.

2.2 Battery Inventor

In the realm of battery invention, notable figures have contributed to its advancements. Benjamin Franklin, a revered inventor in American history, introduced the lightning rod and made improvements to the Franklin stove and bifocal eyeglasses. However, Thomas Edison emerged as a prominent inventor, although he often took credit for earlier discoveries. While Edison did not invent the light bulb, he refined the concept by utilizing a carbonized filament in a better vacuum, making it commercially viable.

Edison's contributions also extend to the phonograph, although Emile Berliner played a crucial role in transitioning from cylinders to discs, allowing for mass production. Eldridge Johnson, a Philadelphia machinist, added a spring motor to the gramophone, enhancing its popularity. Edison's role in the industry was influential, but he faced setbacks, such as losing to Tesla's alternating current (AC) in the electric power source and Berliner's gramophone disc over cylindrical recordings.

The landscape of battery invention remains complex, with research teams and organizations receiving recognition rather than individual inventors. Despite the uncertainties surrounding rightful credit, advancements in battery technology continue to shape our world. Table 2.2 provides a summary of battery advancements and their associated inventors when available.

Year	Inventor	Activity
1600	William Gilbert (UK)	Establishment of electrochemistry study
1745	Ewald Georg von Kleist (NL)	Invention of Leyden jar. Stores static electricity
1791	Luigi Galvani (Italy)	Discovery of ”animal electricity”
1800	Alessandro Volta (Italy)	Invention of the voltaic cell (zinc, copper disks)
1802	William Cruickshank (UK)	First electric battery capable of mass production
1820	André-Marie Ampère (France)	Electricity through magnetism
1833	Michael Faraday (UK)	Announcement of Faraday's law
1836	John F. Daniell (UK)	Invention of the Daniell cell
1839	William Robert Grove (UK)	Invention of the fuel cell (H2/O2)
1859	Gaston Planté (France)	Invention of the lead acid battery
1868	Georges Leclanché (France)	Invention of the Leclanché cell (carbon-zinc)
1881	Camile Alphonse Faure (France)	Invention of lead grid lattice (current system)
1899	Waldemar Jungner (Sweden)	Invention of the nickel-cadmium battery
1901	Thomas A. Edison (USA)	Invention of the nickel-iron battery
1932	Schlecht & Ackermann (Germany)	Invention of the sintered pole plate
1947	Georg Neumann (Germany)	Successfully sealing the nickel-cadmium battery
1949	Lewis Urry, Eveready Battery	Invention of the alkaline-manganese battery
1970s	Group effort	Development of valve-regulated lead acid battery
1990	Group effort	Commercialization of nickel-metal-hydride battery
1991	Sony (Japan)	Commercialization of lithium-ion battery
1994	Bellcore (USA)	Commercialization of lithium-ion polymer
1995	Group effort	Introduction of pouch cell using Li-polymer
1995	Duracell and Intel	Proposal of industry standard for SMBus
1996	Moli Energy (Canada)	Introduction of Li-ion with manganese cathode
1996	University of Texas (USA)	Identification of Li-phosphate (LiFePO4)
2002	University of Montreal, Quebec Hydro, MIT, others	Improvement of Li-phosphate, nanotechnology, commercialization
2002	Group effort	Various patents filed on nanomaterials for batteries

Table 1: **History of modern battery development.** No new major battery system has entered the commercial market since the invention of Li-phosphate in 1996. Big progress was made from 1990 to 2002.

3 Battery Definition

A battery is a device that stores and releases electrical energy through chemical reactions. It consists of one or more electrochemical cells, each composed of two electrodes; a positive electrode (cathode) and a negative electrode (anode) separated by an electrolyte. When the battery is connected to an external circuit, a chemical reaction occurs within each cell, converting chemical energy into electrical energy. The electrons flow from the negative electrode through the external circuit to the positive electrode, generating an electric current. Rechargeable batteries can be reversed by applying an external electrical current, allowing the chemical reactions to be reversed and the battery to be charged again, while non-rechargeable batteries are designed for a single use. Batteries are used in numerous applications, ranging from portable electronic devices and vehicles to power grids and renewable energy systems, providing a reliable and portable source of electricity. Figure 2 illustrates the composition of the alkaline battery, While figure 3 shows compositions of different types of batteries.

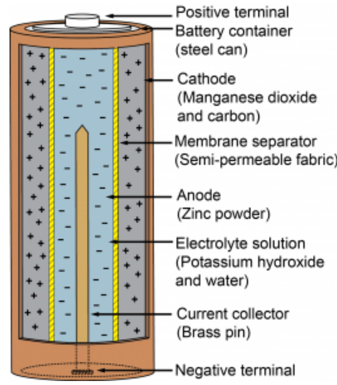


Figure 2: Alkaline battery composition

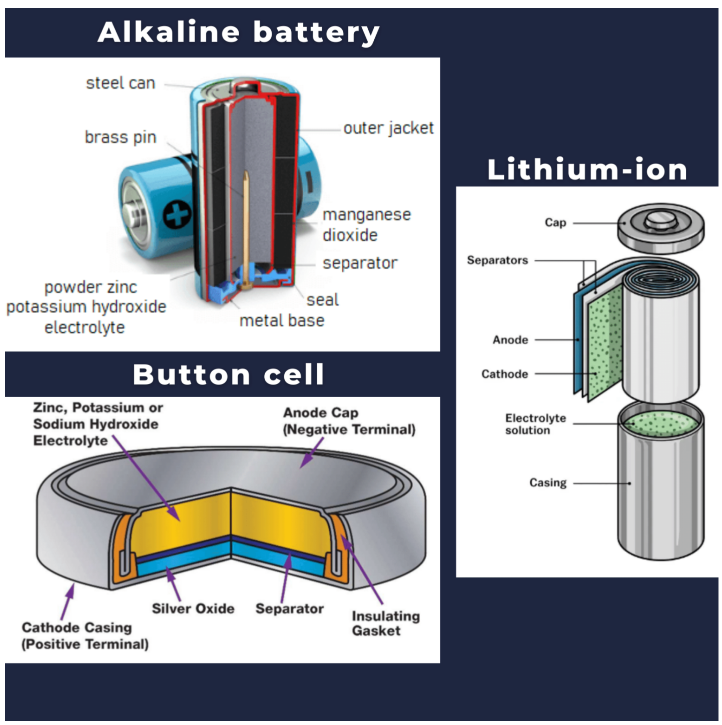


Figure 3: Different types of cells

Battery characteristics are determined by the potentials of the electrodes and the differences between them, which contribute to the terminal voltage. To be practical, a rechargeable battery requires reversible chemical reactions between its elements. Additionally, suitable electrode combinations are limited due to the need to preserve active chemicals. Power, measured in watts, is obtained by multiplying voltage and current, while energy storage capacity is expressed in watt-hours (Wh).

Power, measured in watts, represents the flow of energy at a given moment, while energy is the product of power and time, expressed in watt-hours (Wh). Battery ratings are often specified in ampere-hours (Ah), indicating the amount of charge a battery can hold. The dimensions and weight of a battery are specified in liters (l) and kilograms (kg), respectively, providing metrics such as specific energy (Wh/kg), power density (W/l), and specific power (W/kg). Specific energy is the capacity a battery can hold in watt-hours per kilogram (Wh/kg) while specific power is the battery's ability to deliver power in watts per kilogram (W/kg)

Batteries are designed to meet specific application requirements, with manufacturers focusing on customer needs. Consumer electronics, like mobile phones, prioritize small size, high specific energy, and low cost. On the other hand, industrial batteries aim for reliable performance and extended lifespan. Regardless of the application, safety remains a paramount concern in all battery uses.

3.1 Battery Types

3.1.1 Battery Rechargeability

Batteries can be categorized into two types based on their rechargeability: **Primary Batteries** and **Secondary Batteries**. Primary batteries are designed for single use and cannot be recharged. In contrast, secondary batteries are rechargeable, allowing them to be used multiple times after recharging.

Primary batteries are designed to be used until they are exhausted of energy and then discarded. They are not rechargeable as their chemical reactions are generally not reversible. Once the supply of reactants in the battery is depleted, it ceases to produce current and becomes useless. Some types of primary batteries used in the past, such as those in telegraph circuits, could be restored to operation by replacing the electrodes. However, primary batteries are not meant to be reliably recharged and attempting to do so is generally discouraged by battery manufacturers. Examples of primary batteries include zinc-carbon batteries and alkaline batteries. They are commonly used in portable devices with low current drain, intermittent usage, or when no alternative power source is readily available.

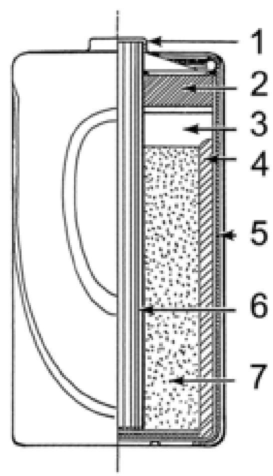
Secondary batteries, also known as rechargeable batteries, can be recharged by applying electric current to the cell. They can have their chemical reactions reversed, allowing them to be used, recharged, and used again multiple times. Rechargeable batteries are typically assembled with the active materials in a discharged state and require charging before their first use. Devices known as chargers supply the appropriate current to reverse the chemical reactions that occur during discharge. One of the oldest forms of rechargeable batteries is the lead-acid battery, commonly used in automotive and boating applications. Lead-acid batteries contain liquid electrolyte in an unsealed container and require proper ventilation due to the hydrogen gas produced during overcharging. Although lead-acid batteries have a relatively high weight-to-energy ratio, their low manufacturing cost and high surge current levels make them suitable for applications where capacity is more important than weight and handling. For example, they are widely used in car batteries, capable of delivering peak currents of around 450 amperes.

3.1.2 Battery Composition

Batteries can be categorized into two primary types based on their rechargeability: **Wet Cell** and **Dry Cell**. There are also other types with varying chemical processes and designs, including galvanic cells, electrolytic cells, fuel cells, flow cells and voltaic piles. In this paper, we only cover wet and dry cells.

A wet cell battery contains a liquid electrolyte and can be referred to as a flooded cell or vented cell. Wet cells were used before dry cells and are often used for educational purposes in demonstrating electrochemical processes. They can be constructed using common laboratory equipment like beakers. Wet cells can be either primary (non-rechargeable) or secondary (rechargeable). Examples of wet cells include the Daniell cell, Leclanché cell, Grove cell, Bunsen cell, Chromic acid cell, Clark cell, and Weston cell. Wet cells are still used in automobile batteries and certain industries but have been replaced by gel cells in many applications. Molten salt batteries, which utilize a molten salt as an electrolyte, are another type of wet cell and operate at high temperatures.

A dry cell, on the other hand, utilizes a paste electrolyte with minimal moisture to enable current flow. Unlike wet cells, dry cells can be used in any orientation without spilling as they contain no free liquid. This makes them suitable for portable devices. The first wet cells were delicate glass containers with hanging lead rods and required careful handling. The safety and portability of dry cells were not achieved until the development of gel batteries. An example of a dry cell is the zinc-carbon battery, also known as the dry Leclanché cell, which has a nominal voltage of 1.5 volts, similar to alkaline batteries. A standard dry cell consists of a zinc anode, typically in a cylindrical pot shape, a central carbon cathode, and an electrolyte paste containing ammonium chloride and manganese dioxide as a depolarizer. In some designs, zinc chloride is used instead of ammonium chloride. Figure 4 illustrate dry cell compositions.



1. Brass cap
2. Plastic seal
3. Expansion space
4. Porous carboard
5. Zinc can
6. Carbon rod
7. Chemical Mixture

Figure 4: Dry cell composition

3.2 Battery Requirements

To be considered viable as an electric storage device, a battery must meet eight basic requirements, giving rise to the term "octagon battery" (Figure 5).

1. **High specific energy**: Consumer products require long runtime, achieved by batteries with high ampere-hour (Ah) ratings. While lithium-ion batteries are known for their high specific energy, not all Li-ion batteries have high Ah ratings. Different applications have different specific energy requirements.

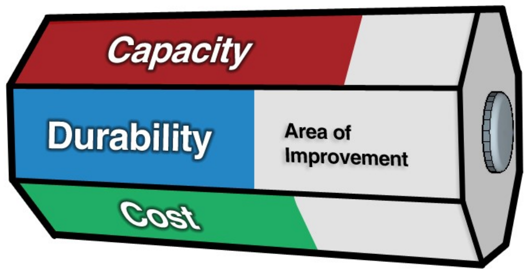


Figure 5: **Octagon Battery**. So-called because of the eight critical requirements needed to achieve basic function. Many new arrivals claim to meet or exceed some prerequisites but fail in others, limiting market acceptance.

2. **High specific power**: Batteries designed for power tools and electric powertrains prioritize high load capabilities over specific energy.

3. **Affordable price**: Battery manufacturing involves costs related to materials, refining processes, manufacturing, quality control, and cell matching. Volume production helps reduce costs, and single-cell use in mobile phones without the need for cell matching also lowers expenses.

4. **Long life**: The longevity of large, expensive battery packs is crucial. Extending the battery life of electric cars from the anticipated 8-10 years to 20 years would justify the initial high investment. Battery life depends not only on design but also on usage conditions such as temperature, charging times, and discharge conditions.

5. **Safety**: Lithium-based batteries offer high specific energy but can be reactive and unstable. Safety concerns have led to the discontinuation of some battery systems. Proper use of brand-name Li-ion batteries ensures safety.

6. **Wide operating range**: Batteries perform optimally at room temperature, as cold temperatures slow down electrochemical reactions. Li-ion batteries cannot be charged below freezing, and high heat shortens battery life and compromises safety.

7. **Toxicity**: Environmental considerations have led to the replacement of cadmium- and mercury-based batteries with alternative metals. Nickel- and lithium-based batteries contain little toxic material but require responsible disposal to avoid hazards.

8. **Fast charging**: Nickel- and lithium-based batteries can be charged quickly, but they must be designed for it, in good condition, and charged at room temperature. Fast charging puts stress on the battery, and charge rates above 1C should be avoided. NiCd batteries can accept ultra-fast charging with minimal stress.

In addition to these eight requirements, batteries should have low self-discharge for long storage and provide instant start-up when needed. Self-discharge increases with temperature and age, and secondary batteries have higher self-discharge rates than primary batteries. Shelf-life and performance degradation are important considerations, as batteries lose capacity over time, even when not in use.

4 Global Battery Market and Advancements

According to The Freedonia Group, the global demand for primary and secondary batteries is projected to reach \$ 156 billion in 2024, with an 8.1% annual growth rate [3]. The market growth is primarily driven by secondary (rechargeable) batteries, which account for a significant portion of the global market and are expected to further increase their market share. This growth is attributed to the rising demand for mobile phones and tablets. However, earlier estimations overestimated the demand for electric vehicles, which has since been adjusted downwards.

4.1 An Overview of Battery Types

In 2009, primary batteries constituted a smaller portion of the global market, and it was predicted that they would experience a decline by 2015. Primary batteries are commonly used in watches, electronic keys, remote controls, toys, flashlights, beacons, and military devices. In terms of battery chemistry, lithium-ion (Li-ion) batteries hold the largest revenue share at 37% and are the preferred choice for portable devices and electric powertrains. Li-ion batteries have maintained their dominance in the market. Figure 6 illustrates the distribution of these chemistries.

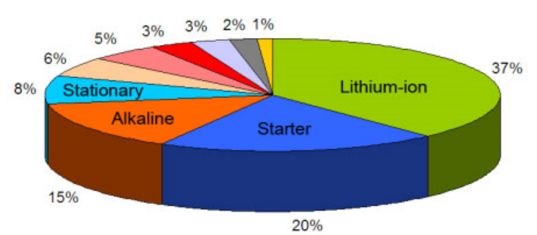


Figure 6: Revenue contributions by different battery chemistries.

1. **37%** – Lithium-ion
2. **20%** – Lead acid, starter battery
3. **15%** – Alkaline, primary
4. **8%** – Lead acid, stationary
5. **6%** – Zinc-carbon, primary
6. **5%** – Lead acid, deep-cycle
7. **3%** – Nickel-metal-hydride
8. **3%** – Lithium, primary
9. **2%** – Nickel-cadmium
10. **1%** – Other

Lead acid batteries continue to be a robust and economical power source for various applications. Despite the growing popularity of Li-ion batteries in the lead acid market, the demand for lead acid batteries is still on the rise. These batteries are used as starter batteries for automotive (SLI), stationary batteries for power backup, and deep-cycle batteries for wheeled mobility such as golf cars, wheelchairs, and scissor lifts.

Alkaline batteries have gained popularity due to their high specific energy and long storage capabilities, surpassing the older carbon-zinc batteries. Nickel-metal-hydride (NiMH) batteries have replaced nickel-cadmium (NiCd) batteries in many applications, but they are now considered a minor player in the market.

4.2 Advancements in Batteries

Batteries are advancing on two fronts, with a focus on increasing specific energy for longer runtimes and improving specific power for high-current load requirements. However, enhancing one characteristic may come at the expense of the other, leading to compromises. Figure 7 illustrates the relationship between specific energy (Wh/kg) and specific power (W/kg) for rechargeable batteries.

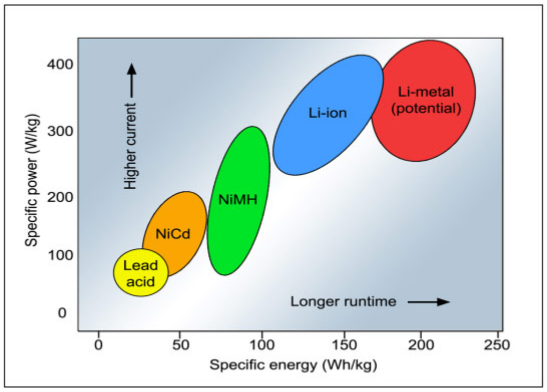


Figure 7: Specific energy and specific power of rechargeable batteries.

The most promising performer in terms of specific energy and specific power is the secondary lithium-metal (Li-metal) battery. Although an early version was introduced in the 1980s by Moli Energy, issues with metallic lithium on the anode led to a recall in 1991 due to dendrite formation causing short circuits. Nonetheless, manufacturers are revisiting this powerful chemistry, exploring solutions such as mixing metallic lithium with tin and silicon, using graphene in the separator, and employing multi-layer separators to prevent dendrite penetration. New experimental Li-metal batteries have achieved 300Wh/kg with even greater potential, making them particularly attractive for electric vehicles

4.3 Challenges and Prospects in Battery Technology Advancements

In the quest for greener energy solutions, batteries have been hailed as a potential liberator from fossil fuel dependency. However, it is crucial to acknowledge that batteries have yet to reach maturity in assuming this critical role. As an electrochemical power source, batteries face limitations such as slow charging, limited energy capacity, short operational lifespans of a few hundred cycles, and eventual disposal challenges.

In contrast to the rapid advancements witnessed in microelectronics, battery technology progress has been relatively sluggish since the commercialization of lithium-ion batteries in 1991 by Sony. While improvements have been made, the rate of capacity increase has been modest at around 8 percent per year, recently slowing down to 5 percent. Encouragingly, costs have been decreasing by 8 percent annually.

Despite ongoing progress, significant hurdles persist. Lithium-air batteries, envisioned in the 1970s with theoretical energy densities comparable to gasoline, have been delayed due to stability and air-purity concerns. Lithium-metal batteries, introduced in the 1980s, still suffer from dendrite growth, posing risks of potential short-circuits and safety hazards. Lithium-sulfur batteries show promise but face challenges in achieving long cycle life. Redox-flow batteries, intended for large-scale energy storage, encounter corrosion issues.

There is a glimmer of hope for enhancing the energy density of lithium-ion batteries by coating the anode with graphene, an ultra-thin one-atom layer. This innovation holds the potential to quadruple energy capacity. However, emerging battery technologies typically take several years to reach commercialization, and a breakthrough solution is yet to emerge.

In pursuit of advancements, initiatives like the Joint Centre for Energy Storage Research (JCESR) bring together leading minds from national laboratories, universities, and private enterprises. JCESR aims to develop a battery that is "five times more powerful and five times cheaper in five years" through a $120 million grant from the US Department of Energy, envisioning the ambitious 5-5-5 Plan.

Toyota also enters the race for a new battery, dubbed the "Sakichi battery" in honor of Sakichi Toyoda, a prominent inventor in Japan's industrial revolution. The battery must surpass the energy output of gasoline while being durable and rapidly rechargeable to claim the yet-unclaimed 1 million yen prize established by Sakichi Toyoda in 1925.

While consumers generally find battery performance satisfactory in portable devices, the success of electric vehicles (EVs) hinges on factors like cost and endurance. Propelling trains, large ships, and airplanes solely with batteries remains impractical due to their weight and limited energy density. Fossil fuels still outmatch batteries in net calorific value by a factor of 100. Conversely, batteries offer clean, quiet, compact, and instantly startable power, making them advantageous in various applications.

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