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The Evolution of Smartphone Battery Technology: From the First Mobile Phone to Modern-Day Devices and Future Advancements

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Abstract: Smartphones have become an integral part of life in this world and play key roles as productivity tools, entertainment, and communication. Also, with these day-to-day improvements in technology, smartphones have evolved to provide strong power with little effort. However, increasing dependence on these has led towards the rising concern about their battery life. With every growing demand for a longer battery life, there has been a great improvement in battery technology. Starting from early models all the way up to today's latest technologies, this study focuses on lithium-ion batteries and a selection of the emerging alternatives. The promising future innovations which include solid-state, sodium-ion, graphene-based, lithium-sulfur, and lithium-silicon batteries are compared against the technology of lithium ions available today and are depicted as bringing about a new revolution in the performance level of batteries as well as extending smartphone usage.

Keywords: Solid-State Battery, Graphene-Based Battery, Sodium-Ion Battery, Lithium-Sulfur Battery, Lithium-Silicon Battery, Lithium-Ion Battery

1. Introduction

Since the first mobile phone was introduced in 1973, smartphone battery technology has advanced significantly. The advancement of smartphone battery technology has fundamentally changed how we use our gadgets and had a big impact on day-to-day living. Figure. 1 depicts the chronology of smartphone battery technology development, starting with the initial mobile phone and ending with current models [1, 2]. In 1973, Motorola released the DynaTAC, the first mobile phone. It only had a thirty-minute speaking time and weighed close to 2.5 pounds. The nickel-cadmium (Ni-Cd) battery that was utilized in this phone was large and had a low energy density. Additionally, if these batteries weren't completely drained before recharging, they would lose their ability to hold a charge due to a phenomenon known as the "memory effect". Ni-Cd batteries were initially introduced in 1899 and had an energy density of 40–60 $Wh.kg^{-1}$ and a charge and discharge density of 70–90%. The specific power stands at 150 $Wh.kg^{-1}$. Nickel-Metal Hydride (Ni-MH) batteries caused a revolution in energy storage tech when they hit the scene in 1949. These batteries started with an energy density of 60–120 $Wh.kg^{-1}$ and charge and discharge efficiency of 66–92%. Over time, the performance of these batteries has gotten better. Now, their specific power falls between 250 and 1000 $Wh.kg^{-1}$. Since hitting the market in 1992, Ni-MH batteries have been the go-to choice for portable gadget power sources [3]. Ni-MH batteries outperform Ni-Cd batteries in several ways: they pack more energy last longer, and cause less harm to the environment. The IBM Simon launched in 1993, made history as the first smartphone to feature a removable battery. This increased the duration that customers could use their phones by enabling them to carry an additional battery and replace it when the original one ran out of power [4]. At present Lithium-ion (Li-ion) batteries have become the standard power source for smartphones. The first Li-ion battery was commercially released by Sony in 1991[5]. Li-ion batteries offer significant advantages, including a high energy density ranging from 100 to 265 $Wh.kg^{-1}$ and power densities of up to 340 $W. kg^{-1}$ [6]. Additionally, Li-ion batteries do not suffer from the "memory effect" [7, 8]. This absence of memory effect in Li-ion batteries allows users to recharge them at any point, without compromising their performance. These batteries also support 500 to 1,000 charge cycles before experiencing significant degradation, ensuring 2-3 years of usage in typical consumer applications [9]. Their combination of lightweight design, high energy density, and long cycle life makes them the preferred choice for mobile power and energy storage applications. After being released in 2001, lithium-polymer (Li-Po) batteries swiftly replaced other batteries as the standard for cellphones. These batteries were perfect for smaller and thinner cellphones since they provided a better energy density and were lighter overall. The initial iPhone, released by Apple in 2007, had a Li-Po battery that was fixed in place [10, 11]. Due to the desire for a more streamlined design, non-removable batteries were chosen by the majority of smartphone makers, starting a trend in the industry. The demand for faster-charging technology arose as cellphones got more potent and power-hungry. Qualcomm unveiled Quick Charge in 2013; with this technology, smartphones may charge up to 75% quicker than with more conventional charging techniques. Users may now charge their cellphones wirelessly, eliminating the need for wires, thanks to technology that was initially launched in 2015. Through the use of electromagnetic induction, energy is transferred from a charging pad to the phone's battery using this technique [12]. Considering the state of smartphone battery technology going forward, graphene batteries were introduced. These batteries can be charged considerably faster and have a substantially better energy density than conventional Li-ion batteries [13]. The battery life of cellphones has significantly improved in recent years. Artificial intelligence (AI) is being used by manufacturers to maximize battery efficiency and prolong battery life. Furthermore, cellphones are starting to use bigger, higher-capacity batteries more frequently [14]. The emergence of foldable gadgets has led to improvements in battery technology. To enhance the performance of mobile phones' batteries, manufacturers are progressively using innovative materials like lithium-sulfur [15]. These phones demand flexible and robust batteries. An adequate amount of study articles has already been published on the batteries used in mobile phones, both the Li-ion and Li-Po batteries used now and the Ni-Cd and Ni-MH batteries used in the past. This work aims to present an overview of the next generation of batteries that will be utilized in smartphones, including silicon anode batteries, graphene-based batteries, sodium-ion batteries, solid-state batteries, and lithium-sulfur batteries. Examining the advantages and difficulties of using the aforementioned future batteries in mobile phones is compared with the current Li-ion battery.

2. Solid-State Batteries

A type of rechargeable battery known as a solid state battery uses solid electrolytes rather than liquid or gel-based electrolytes. This distinguishes them from conventional lithium-ion batteries, which have a liquid electrolyte and are used in mobile phones [16]. This liquid electrolyte can shorten the life of the battery by causing corrosion and leaks in addition to being flammable. However, a solid electrolyte is used in solid state batteries, which is more energy dense, increased working temperatures, longer longevity and safer [17, 18].

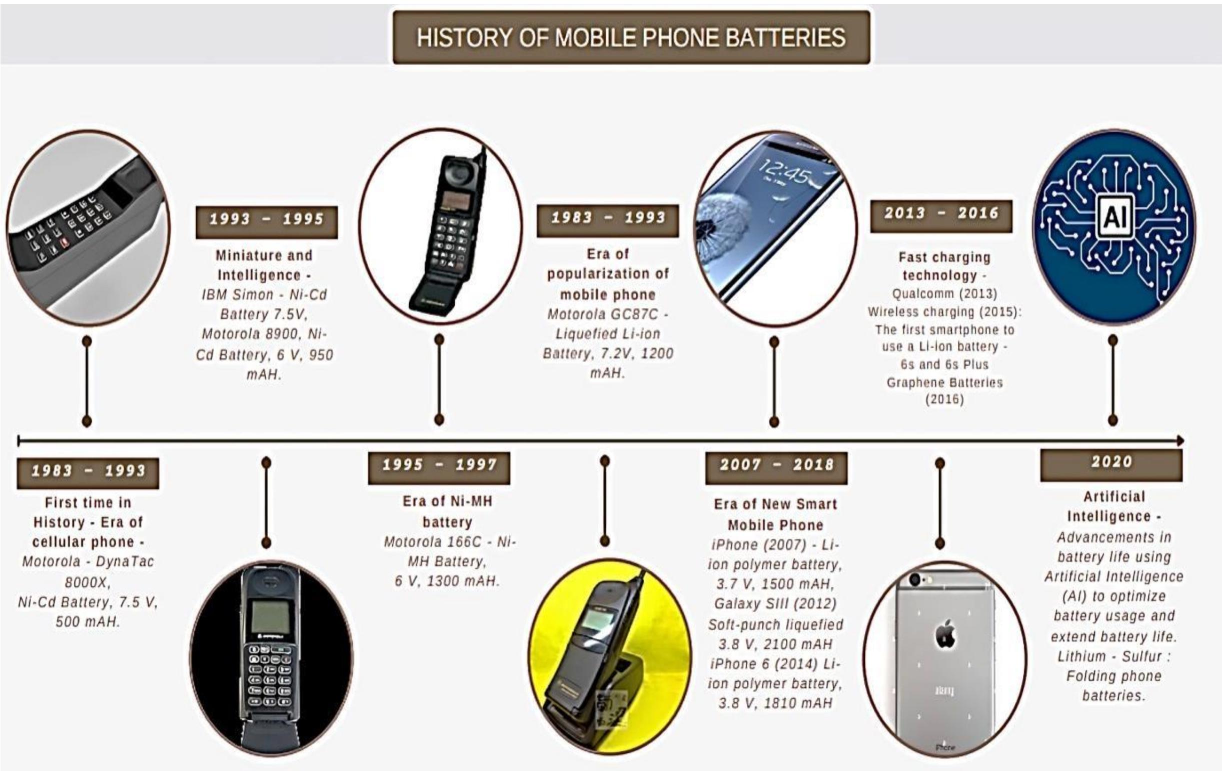

Figure 1. Chronology of smartphone battery technology development

The anode of solid-state batteries is frequently composed of materials containing lithium, such as lithium metal or alloys. Lithium foil and lithium-containing substances like lithium titanate ($Li_4Ti_5O_{12}$) are examples of common materials. During discharge, the solid-state electrolyte permits lithium ions to move from the negative electrode to the positive electrode. A metal oxide, such as lithium cobalt oxide ($LiCoO_2$), lithium iron phosphate ($LiFePO_4$), or comparable compounds, usually makes up the cathode of a solid-state battery, much like it does in a traditional Li-ion battery [19]. The battery's performance parameters, such as energy density, voltage, and safety, are impacted by the cathode material selection. Lithium ions are conducted between the anode and cathode of solid-state batteries via the electrolyte, a solid substance. Solid-state electrolytes can be made of composites, polymers, or ceramics, among other materials. Polymers like polyethylene oxide (PEO) doped with lithium salts, oxides like lithium lanthanum titanate (LLTO), sulphides like lithium thiophosphate (Li_3PS_4), and lithium phosphorus oxynitride (LiPON) are common solid-state electrolyte materials.

2.1 Mobile Companies Using Solid State Batteries

Solid state batteries are now being used by a number of significant mobile manufacturers in their products. Xiaomi was among the first businesses to incorporate solid state batteries into its products. The solid state battery-powered Xiaomi Mi 9 smartphone was introduced in 2019. This 3,500mAh battery may be charged from empty to full capacity in about 17 minutes. This was a significant improvement over traditional lithium-ion batteries, which take an hour or two to fully charge. Solid state battery development has also been a focus for Samsung. In 2020, Samsung claimed to have invented a solid state battery with a capacity of 900 Wh/l, about double the energy density of standard lithium-ion batteries. Upcoming gadgets from Samsung, such as electric cars and smartphones, are anticipated to employ this battery. An allegedly more energy-efficient, quicker-charging, and safer solid-state battery is being developed by Samsung. The new technology is scheduled for release by Samsung in 2027 [20].

Solid state battery research has also been undertaken by Apple, one of the top mobile businesses globally. A business that specializes in creating solid state batteries, SiliCon Power, was purchased by Apple in 2019. The acquisition strengthened Apple's hold on this technology. Solid state batteries are reportedly being used by Apple in its next-generation gadgets, which could improve the devices' battery life and charging speed. Several mobile businesses are creating solid-state batteries for their smartphones, including Solid Power, Samsung, Toyota, and BMW [21].

2.2 Impact on the Mobile Industry

Solid state battery technology in mobile devices has the potential to drastically alter the market. A significant benefit of solid state batteries is their extended lifespan. Traditional lithium-ion batteries are not as long-lasting as solid state batteries which begin to deteriorate after 500–1000 charge cycles [22]. This will save consumer costs and electronic waste since customers won't need to replace their batteries as frequently.

Furthermore, the energy density of solid state batteries is higher, allowing them to store more energy in a given amount of space [23]. Because of this, mobile phone firms will be able to reduce the thickness and weight of their gadgets without sacrificing battery life. Moreover, customers will save a great deal of time because to solid state batteries' quick charging characteristics.

The environment will benefit from the adoption of solid state batteries as well. Because of their longer lifespan—which was previously mentioned—fewer batteries will wind up in landfills or incinerators. Moreover, using solid state batteries will lessen the need for lithium, a mineral that is scarce and harmful to the environment [24].

2.2 Challenges in implementing solid-state batteries in mobile phones

Even with solid-state batteries many benefits, a few issues still need to be resolved before they can be widely utilized in mobile phones. The cost of using solid-state batteries in mobile phones is one of the biggest obstacles. It is currently more expensive to produce solid-state batteries than Li-ion batteries, which makes it challenging for manufacturers to incorporate them into their products without raising the total cost.

This presents a significant challenge because customers are unlikely to pay a substantial premium for a phone that uses a solid-state battery, particularly if they are already happy with the functionality of their current handsets that run on lithium-ion batteries [25].

The scalability of solid-state batteries is another significant challenge. Although they have been effectively produced in lab settings, scaling up production to satisfy the market's expectations for mobile phones remains a difficulty. This calls for major modifications to manufacturing procedures in addition to large expenditures in research and development. Furthermore, it is challenging to make solid-state batteries on a wide scale due to the incomplete establishment of their supply chain [26, 27].

The robustness and lifespan of solid-state batteries are additional issues. They may have a longer lifespan than lithium-ion batteries, although study and development on them remain in their early stages. It is crucial to make sure they can tolerate the rigors of regular use, such as temperature fluctuations and physical strain from being carried about in a pocket or purse. The goal of having a longer-lasting battery may be ultimately defeated if these batteries are not strong enough and need to be replaced more frequently. Solid-state batteries continue to raise safety questions, too. They do not completely eliminate risk, even though they are less likely to overheat and explode than lithium-ion batteries [28]. These batteries may develop dendrites as a result of using solid electrolytes, which may result in short circuits and maybe a fire. With mobile phones in close proximity to their users all the time, safety concerns are quite important because they could have serious repercussions. In conclusion, solid-state batteries have a lot of potential to change the battery business, but in order for them to be successfully incorporated into mobile phones and other electronic devices, these obstacles must be resolved [29].

3. Sodium-Ion Battery

Sodium batteries are rechargeable batteries that utilize sodium ions rather than lithium ions as the charge carrier. The primary distinction between the two is that sodium is used in place of lithium. The scientific and commercial interest in sodium ion batteries in the 2010s and 2020s was influenced by the unequal distribution across the globe, considerable environmental effect and high cost of many of the ingredients needed for Li-ion batteries. When it comes to producing batteries, sodium is a more affordable and plentiful element than lithium, which makes it a more economical and ecological choice. Moreover, sodium batteries come with a lower chance of thermal "runaway," setting them up as a safer choice [30]. Sodium-ion cells consist of an anode made from materials like hard carbon, graphite, tin, manganese disulphide, graphene, or carbon arsenide. In these batteries, the cathode is a material that can absorb sodium ions during charging and release them during discharging. This crucial role is frequently played by substances like sodium transition metal oxides ($NaCoO_2$ $NaFePO_4$) and polyanionic compounds ($Na_3V_2(PO_4)_3$, $Na_2Ti_3O_7$). Sodium transition metal polyphosphates ($Na_3V_2(PO_4)_3$, $Na_2Ti_3O_7$), sodium transition metal oxides ($NaCoO_2$, $NaFePO_4$, Na_2FePO_4F) and organic compounds such polyaniline derivatives are examples of anodically appropriate cathode materials. In a sodium-ion battery, electrolytes are commonly composed of sodium salts dissolved in a solvent, such as sodium hexafluorophosphate ($NaPF_6$), sodium perchlorate ($NaClO_4$), sodium tetrafluoroborate ($NaBF_4$), and sodium bis-trifluoromethyl sulfonyl amid (NaTFSI). Propylene carbonate (PC) and ethylene carbonate (EC), which are also utilized in lithium-ion batteries, are among its constituent organic carbonates [31]. However, sodium-ion batteries can occasionally be used with solid or aqueous electrolytes.

3.1 Benefits and Limitations of Sodium-ion Batteries in Mobile Devices

One of the primary advantages of sodium-ion batteries is their cost, which is much lower than that of Li-ion batteries. Sodium is a much more abundant element than lithium. Thus, their productions costs are significantly lower [32]. Therefore, producers will be able to pass the cost savings in production on to consumers in the form of more affordable mobile phones. Moreover, sodium-ion batteries are less dangerous to the environment than lithium-ion batteries. Since sodium can be extracted from sea water, it is also a more renewable and sustainable resource compared to lithium-ion batteries that require rare earth elements to be mined and processed. This reduces the impact of battery production on the environment and makes disposing of these batteries at the end of their useful lives [33].

Actually, the highly reactive nature of the lithium-ion batteries has caused numerous fires or even explosions, which is not found in sodium-ion batteries. For this reason, it can safely be used on mobile phones, as sodium is more stable and less reactive compared to lithium. Still, sodium-ion batteries have certain drawbacks in addition to these benefits. They have a lower energy density and shorter cycle life than lithium-ion batteries, which is one of the primary problems [34, 35]. As a result, mobile phone batteries made of sodium-ion may not be able to store as much energy as those made of lithium-ion. For customers who use their phones frequently during the day, this could be a significant disadvantage.

4. Graphene-Based Batteries

Graphene is a carbon allotrope with remarkable electrical, chemical, and physical properties that takes the form of a hexagonal (honeycomb) lattice structure. It is flexible, lightweight, and has a huge surface area. It also is an excellent electrical conductor. Such a substance fits the bill well for batteries because of these attributes. As for the basic architecture of batteries, graphene-based and lithium-ion ones are very much alike. There is an anode, cathode, and electrolyte common to all, but the content of the anode differs considerably. Graphite is used as the anode material in lithium-ion batteries, but it utilizes graphene for more effective graphene-based batteries. In addition to having an energy density of 240 $Wh.kg^{-1}$, graphene batteries also have a charge and discharge density that varies between 90–95% [36].

Comparing graphene-based batteries with other energy storage technologies and traditionally used lithium-ion batteries reveals a number of benefits. A few of the significant benefits include:

- ***High Energy Density:*** Graphene-based batteries are potentially capable of achieving higher energy densities than conventional lithium-ion batteries. Since batteries can store more energy per unit volume, they will last longer and function better.
- ***Fast Charging:*** Since graphene possesses special qualities, it can charge more quickly. Its high conductivity and surface area allow the speedy movement of electrons, which speeds up battery charging in comparison to conventional batteries.
- ***Extended Life:*** Graphene also lengthens battery life by mitigating electrode decay. Because it exhibits mechanical strength and chemical stability, batteries take a longer lifespan with less chance of structural destruction and electrolyte breakdown. Graphene-based batteries also will last for a much longer time that decreases the electronic waste generated from battery replacements by its extended period of use [37].
- ***Enhanced Safety:*** Improved Safety: Graphene's chemical and thermal stability could contribute to a safer battery operation. High thermal conductivity helps dissipate heat more efficiently, reducing the danger of thermal runaway and fires in batteries. Additionally, materials based on graphene can be engineered to reduce dendrites' propensity, which causes short circuits and leads to safety risks.
- ***Flexibility and Lightweight:*** Flexibility and Lightweight: The flexibility and light weight of graphene make it appropriate for flexible and portable electronics applications. Graphene-based batteries can be used in flexible devices to enable new form factors and applications in wearable technology, flexible displays, and so on.
- ***Environmental Sustainability:*** Graphene-based materials are potentially less harmful to the environment than conventional batteries. Graphene is an extremely abundant material, and the production processes can be more environmentally friendly than those of some other battery materials. Moreover, the wider recycling opportunity and much longer lifespan of graphene-based batteries further contribute to sustainability. Hence, altogether, the overall promise that graphene-based batteries offer for revolutionizing energy storage is nothing but tremendous performance, safety, and sustainability across a wide range of applications [38, 39].

4.1 Graphene Battery Challenges for Mobile Phones

Despite their promise, there are still a few issues that must be addressed before graphene-based batteries can be widespread in mobile phones. The cost of manufacture is one of the main challenges. Graphene is still a new material and manufacturing is expensive. The producers of mobile phones have to be able to afford graphene-based batteries, so this has to be brought down [40]. Stability in graphene-based batteries is also a challenge. While they have shown promising results in the lab, much development and research has to be done before they can be understood and improved to function in real life. This includes performance in very long operations and extreme temperatures. A smartphone that has come closest to realizing the full promise of a graphene-based lithium-ion battery is the Xiaomi Mi 10 Ultra, which was introduced in 2020 and revolutionized efficiency and charging speeds. This phone can achieve 41% charge in just 5 minutes and reach a full charge in 23 minutes thanks to its amazing 120W charging capability. With continued research and development aimed at enhancing its performance and lowering production costs, the future of graphene-based batteries in mobile phones is bright [41].

Companies like Samsung SDI (South Korea), Huawei Technologies Co. Ltd. (China), Log 9 Materials Scientific Private Limited (India), Cabot Corporation (US), Grabat Graphenano Energy (Spain), Nanotech Energy (US), Nanotek Instruments Inc. (US), XG Sciences Inc. (US), ZEN Graphene Solutions Ltd. (Canada), Graphene NanoChem (Malaysia), Global Graphene Group (US), Vorbeck Materials Corp. (US), Global Graphene Group (Spain), Hybrid Kinetic Group Ltd. (Hong Kong), and Targray Group (Canada) are manufacturing graphene-enhanced batteries. Table I displays a comparison of the current generation of Li-ion batteries with a number of future battery types, including solid-state, graphene-based, and sodium-ion models.

5. Lithium-Sulfur Batteries

Rechargeable batteries that use sulfur as the cathode and lithium as the anode are known as Lithium-Sulfur (Li-S) batteries. They have a far better energy density and low cost than traditional Li-ion batteries, which makes them a good choice for many applications, including mobile phones [42].

5.1 History of Li-S battery

Early in the 1990s, Canadian researchers at the University of Waterloo created the first prototype of a Lithium-Sulfur (Li-S) battery for use in portable electronics. However, because of its short cycle life and inconsistent performance, the technology was not yet economically feasible. Companies like IBM and Sion

Power Corporation began investing in the development of Li-S batteries for mobile devices in the early 2000s due to the rise of smartphones and the growing demand for longer battery lives [43]. In addition to elongating the lifespan of a battery and shortening the recharging time, Li-S battery application in cell phones has resulted in a big impact on the environment. The increasing use of Li-S batteries in mobile phones has faced obstacles despite their many benefits. Due to its relative youth, the technology still has to be researched and developed further in order to address problems like poor cycle life and safety concerns. However, because of ongoing scientific advancements and expenditures, it is projected that Li-S batteries will remain an essential aspect of the powering upcoming mobile phones. Li-S batteries will advance along with technology, opening the door to a more eco-friendly and productive future for mobile devices.

Li-S batteries are capable of having five times the energy density of lithium-ion batteries, which translates to a longer lifespan. The Sulfur cathode, which has a theoretical specific capacity of 1675 mAh/g, is far more effective than the cobalt-based cathode, which has a specific capacity of 372 mAh/g and is commonly employed in lithium-ion batteries. A potential energy buildup of 2600 $Wh.kg^{-1}$ has been found through simulation using this kind of battery [44, 45].

Li-S batteries have a higher potential energy density, which may result in smartphones that are lighter and thinner and have longer battery lives. But Li-S batteries have a short cycle life, which means that they are not as good for smartphones, since consumers frequently charge their gadgets every day [46]. Due to their shorter lifespan, Li-S batteries would require more frequent replacement, which would incur more expenditure for users. Though Li-ion batteries might not have the same high energy density as Li-S batteries, they are a more sensible option for smartphones due to their stable chemistry and longer lifespan. Their ability to withstand daily cycles of charging and discharging is noteworthy, as it guarantees a dependable and enduring power supply for electronic gadgets. Research and development are being done to address the short cycle life of Li-S battery and novel designs and materials are being investigated [47].

5.2 Li-S Battery Breakthroughs

Major Companies Involved in the production of LI-S batteries are PolyPlus Battery Company (US), NexTech Batteries Inc. (US), Li-S Energy Limited (Australia) Lyten, Inc. (US), Zeta Energy LLC (US), Theion GmbH (Germany), Gelion plc (Australia), Hybrid Kinetic Group (Hong Kong), Adeka Corporation (Japan), and others. The US Department of Energy has granted $4 million to the US company Zeta Energy to further develop Li-S batteries.

6. Lithium–Silicon Battery (Or) Silicon Anode Batteries

A silicon-based solid electrolyte, solid cathode, and solid anode comprise one type of rechargeable lithium-ion battery known as a solid-state silicon battery or silicon-anode all-solid-state battery. Mobile phones are among the many uses being investigated for silicon anode batteries, a promising technology. While graphite is the anode material used in conventional Li-ion batteries, silicon anodes have a number of potential benefits [48]. Li-ion batteries have some competition from silicon anode batteries, which seem like a promising substitute. Compared to graphite, which is frequently utilized in Li-ion batteries silicon has a far higher energy density, which allows it to store more energy in the same volume of space. This makes it a perfect fit for smartphones because of its feature to offer a longer period of battery life [49]. Because silicon is lighter than graphite, the batteries made from silicon are more portable and lighter as well, which is beneficial for the users that don't have access to charging stations for long periods of time. Its ability to degrade with time is one of the major drawbacks of Li-ion batteries. Li-ion batteries tend to lose capacity as they are frequently charged and discharged, which means their lifespan is reduced. This "battery degradation" is of course a major concern for consumers of mobile phone. As a result, the batteries have to be replaced very frequently by the users, which can be pretty expensive and irritating. But actually silicon anode batteries have a longer lifespan than Li-ion. In fact, due to higher stability silicon is less likely to degrade [50]. Another disadvantage is the safety issues around Li-ion batteries. These batteries can explode or catch fire due to damage or exposure to high temperatures. Smartphone manufacturers have made many safety precautions for their devices because it has been an important concern to them. It is observed that silicon anode batteries have reduced risk of catching fire or bursting, which were seen to have greater stability in nature. Hence, they would be used for more safe phones [51]. Despite promising advantages for silicon anode batteries, their applications in cellphones remain relatively new. The surface of a silicon anode develops an unstable solid-electrolyte interphase layer after cycling, which contributes to further capacity loss and deterioration of the battery. To stabilize the Solid-Electrolyte Interphase layer and prevent capacity loss, the electrolyte composition may be modified. Poor coulombic efficiency causes irreversible capacity loss in the first cycles of charging and discharging of silicon anode batteries [52].

This is primarily due to the impossibility of implanting silicon inside the battery. Silicon expands as well as shrinks when recharging and then releasing; cracking and structural breakage are observed in the cell, leading over time to reduction in the capacities and performances [50]. To address the problems, different silicon anode stabilizing functionalities by producers can improve its properties like silicon-carbon composites, nanostructuring etc. Sil-ICON could enhance the anodic stability along with coulombic efficiency while being coupled to other material of carbon or graphene [53]. The price per unit volume production of Lithium-silicon batteries are highly expensive comparing lithium-ion in contemporary times [54]. Research and development efforts are being conducted to find more economical means of generating these batteries as the demand for them grows.

6.1 Silicon Anode Battery Breakthroughs

Mobile phones could benefit greatly from the use of silicon anode batteries, which have the potential to provide much longer battery lives and quicker charging times [55]. We anticipate seeing a broad use of silicon anode technology in mobile devices in the upcoming years as the obstacles related to it are resolved. Battery innovation has long been exhibited by Xiaomi and the Mi line of smartphones. With the help of Mi Turbo Charge technology, the Xiaomi Mi 10 Ultra (which was released in April 2021 and is featured in the TechInsights Battery Essentials membership) allows for 120 W wired charging. With two 2250 mAh cells connected in series for quicker wired and wireless charging, the battery is a double-cell, butterfly design. By dividing up the charging flows, the battery cells are not subjected to the entire 120 W load; instead, just 60 W is applied to each battery.

Using Silicon as anode or silicon based nanomaterials advances the battery technology by improving performance, reliability and Safety and an alternative to traditional materials [56, 57]. Although the Xiaomi Mi 11 Ultra has a conventional battery configuration, it has unique cell chemistry with an Amperex Technology Limited (ATL) graphite/Si anode and a cobalt oxide-based cathode. According to Xiaomi, this smartphone is the first to use a second-generation nano-silicon anode material, which has a ten-fold larger capacity than conventional graphite anode cells. It is claimed that the battery will charge to 100% at a rate of 67 watts (both wired and wireless) in 36 minutes. The Magic 6 Pro, Honor's newest flagship phone, was first released in China in January 2024. With its innovative battery technology, the Honour Magic 6 Pro can charge its 5,600mAh battery from 8 to 100 in less than 40 minutes, all without the need for additional bulk or weight. The Magic 6 Pro's battery is unquestionably its standout feature. Compared to lithium-ion batteries with anodes made entirely of carbon or graphite, it can store more energy at the same density because to its silicon-carbon anode. Because of this, Honor's flagship phone is able to accommodate a 5,600mAh battery without being any heavier or bulkier than its competitors. Additionally, compared to existing lithium-ion batteries, the new battery technology is less susceptible to low temperatures, which often results in lower voltages and less energy. A newly designed battery controller chip will provide more accurate charge indications under various scenarios. The battery can charge from 0 to 100 in less than 40 minutes, because to the fast speed of 80W with the supplied charger or 66W wirelessly with Honor's optional charging pad.

A comparison of the Li-ion battery with future batteries is shown in Table 1.

Table 1. Comparison of the Li-ion battery with future Batteries

Feature	**Lithium-Ion Battery**	**Sodium-Ion Battery**	**Graphene-Based Battery**	**Solid-State Battery**	Lithium-Sulfur Battery	Lithium-Silicon Battery
Energy Density (Wh.kg^{-1})	High	Lower than Li-ion	Very high	Very high	Very high, but theoretical	High to very high
Safety	Generally safe, but risks of overheating and thermal runaway under extreme conditions	Safer, more stable, lower fire risk compared to Li-ion	Safer than Li-ion due to better heat dissipation, but still developing	Higher safety due to solid electrolytes; reduced risk of fire or thermal runaway	Lower stability, prone to dendrite formation, fire risks.	Generally safer than Li-S, but still faces issues like volume expansion leading to potential failure over time.
Lifespan (Cycles)	High	Moderate lifespan	Potentially higher lifespan due to reduced wear from charge cycles	Long lifespan, though still under research)	Shorter lifespan	Longer lifespan

Cost	Moderate; declining due to mass production	Lower cost due to the abundance of sodium but slightly higher due to lower development maturity	Likely to be expensive due to new materials and manufacturing processes	High, due to complex manufacturing and new materials	Low-cost materials (sulfur), but higher manufacturing costs due to complex stabilization requirements.	Likely to be more expensive than Li-ion due to silicon's limited use and technological challenges in stabilization.
Technology Readiness	Fully commercialized and widely available	Early stages of commercialization with increasing research interest	Experimental, not yet fully commercialized; promising for future high-performance applications	Still in research and development, but closer to commercialization in certain applications	Experimental, not yet fully commercialized; being developed for niche markets.	Early-stage commercialization, with active research and some near-future potential.
Performance Consistency	Good, stable performance across a wide range of conditions	Lower than Li-ion; performs worse in cold environments	High potential for consistent performance due to enhanced conductivity and fast electron mobility	Very consistent due to solid-state construction, high stability	Inconsistent, tends to degrade rapidly after fewer charge cycles.	Potential for high performance, but currently limited by challenges such as silicon expansion causing cracks.
Environmental Impact	Recycling issues, reliance on scarce materials (e.g., cobalt, lithium)	Environmentally friendly, abundant materials, lower environmental footprint	Better for the environment, graphene is recyclable, but still requires mining of lithium	Environmentally friendlier due to non-toxic, solid electrolytes and lack of flammable components	Environmentally friendly materials (sulfur) but short lifespan increases waste.	Lower environmental impact compared to Li-ion but still under research for large-scale viability.
Charging Speed	1-2 hours (depending on capacity and fast-charging technology)	Similar to Li-ion; slightly slower charging speed	High potential for ultra-fast charging (minutes), though still under development	Can support fast charging; could be much faster than Li-ion depending on electrolyte material	Faster charging potential, but technology is still developing to manage degradation.	High potential for fast charging, though current iterations still struggle with long-term consistency
Form Factor	Flexible, lightweight, and compact designs	Similar to Li-ion but larger and bulkier due to lower energy density	Potential for thin, lightweight designs with high conductivity	Potentially thinner designs due to high energy density and compact solid-state construction	Similar form factors possible, but overall heavier due to the need for stabilizers and current experimental designs.	Similar to Li-ion with future potential for thinner designs due to higher energy density.

The following conclusions are drawn from Table I.

- ***Lithium-Ion Battery*** is the most mature and widely used technology, providing good energy density, safety, and reasonable cost but has environmental concerns.
- ***Sodium-Ion Battery*** is promising for low-cost, eco-friendly alternatives but lags in energy density and performance compared to Li-ion.
- ***Graphene-Based Battery*** hold immense potential for higher energy density and faster charging, though they're still experimental and expensive.
- ***Solid-State Battery*** offer superior safety, energy density, and long lifespan but are still in the research phase and are costly to produce.
- ***Lithium-Sulfur Battery*** offers a high energy density potential but struggles with lifespan, safety, and commercial readiness.
- ***Lithium-Silicon Battery*** shows promise with high energy density and improved environmental impact, but there are challenges with performance consistency and safety.

7. Conclusion

Therefore, in order to satisfy the needs of current times for increased performance, sustainability and efficiency, future mobile phone battery technologies are at the forefront of change with persistent innovation. Current applications on the mobile devices are an integral portion of our lives since they drive communication, business, entertainment, health care, and newly emerging technologies such as augmented reality and AI-the current Li-ion battery does have severe drawbacks. Future battery technologies such as Solid-State Batteries, Graphite-based designs, Sodium-Ion, Lithium Sulfur, and Lithium silicon's chemistries represent gargantuan developments addressing serious issues like energy density, charge times, safety, and environmental impact.

For instance, the solid-state battery will possess greater energy density, lesser overheating risks, and little risk of explosion when charged. The near future graphene-based batteries will be ultra-fast charging speed and longer lifespan due to far better conductivity and strength properties. Sodium-ion is another developing technology that possesses much abundant lithium but sold at cheaper prices. Lithium-sulfur and lithium-silicon design pushes the boundary on the possible energy storage reserve within the battery, making it suited for power-hungry applications in future smartphones.

In addition, this trend toward next-generation battery technologies manifests a broader emphasis on sustainability. In fact, these technologies will reduce dependence on rare or harmful-to-the-environment materials and increase recyclability, hence helping towards the building of an eco-friendlier future. In this context, in the market of mobile devices around the world, there remains a lot of room for solutions in harmony with energy demands that don't hasten the degradation of the environment.

Lastly, the mobile phone battery will prolong or even shift the lifeline and functionality of devices. This will all of a sudden change the entire mobile industry as it now allows for newer device designs: thinner, lighter, and also more energy-efficient while the capability of mobile technology is improved in terms of its support on advanced features like 5G, AI, and beyond. In an increasingly portable technology-dependent world, better battery solutions represent not just development but necessity propelling innovation and sustaining the rhythm of technological development in savvy and environmentally friendly, robust, and user-centric ways.

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S. Manoharan: Methodology, Data collection, Analysis, Writing & Original draft; B. Mahalakshmi: Conceptualization, Supervision, Validation, Writing, Review & Editing; K. Ananthi: Writing, Review & Editing; P. Palpandian: Writing, Review & Editing; K. Balachander: Writing, Review & Editing; All authors read and approved the final manuscript.

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Data Availability

The data supporting the findings of this study can be obtained from the corresponding author upon reasonable request.

Has this article screened for similarity?

Yes

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