# GRAPHENE BATTERIES AND THE FUTURE OF ENERGY STORAGE

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***Abstract—****Batteries are integral to our modern world, serving as essential components in innumerable devices. However, as technology advances, limitations in battery systems—primarily resulting from the composition of the battery's electrodes—have caused them to hinder rather than enable innovation. Additionally, the materials used in the common lithium ion battery present several issues of sustainability, including resource depletion and the introduction of environmental and human health hazards. Consequently, a focus of contemporary research has been on creating more effective designs and finding materials with more desirable qualities to be used in batteries. One such material is graphene, a sheet of carbon atoms bonded together in a honeycomb-lattice pattern exactly one atom thick. With several desirable qualities, including a large surface-area-to-mass ratio, high conductivity resulting from high electron mobility, and incredible intrinsic strength, graphene holds great potential for applications in the energy industry.*

*Although there are major obstacles to extensive graphene use, including the difficulty of producing graphene to a commercial scale, methods have been suggested that can potentially be used for mass production. Unlike the production of the materials currently used in the electrodes of lithium ion batteries, these mechanisms are not resource intense, which lends to both the economic and environmental sustainability of graphene batteries. While graphene batteries and graphene-enhanced batteries are currently not widely used, numerous variants have been developed. Many of these display larger energy densities and longer battery life-span. Samsung has created a "graphene ball" battery that might potentially be used to enhance their future devices. This battery, with a higher charge capacity, faster rate of charge, and greater temperature tolerance, coupled with an accompanying method of production, presents an opportunity for graphene batteries to become widespread. Ultimately, the success of this battery could result in application in many other fields beyond personal electronics, including use in electric vehicles and biomedical devices, demonstrating the potential impact of graphene batteries and their ability to drive sustainable innovation.*

*Key Words—Graphene, Capacity, Electrode, Power (Specific Power) Density, Energy (Specific Energy) Density, Electron (Carrier) Mobility.*

## THE INFLUENCE OF BATTERIES AND THE DEMAND FOR GREATER BATTERY PERFORMANCE

Rapid innovation over the past several decades has led to increased proliferation of electrically-powered technology. These technologies have profoundly impacted our lives and as such, have become integral parts of our society. While many devices are powered by direct connections to an electric grid, many more can only fulfill their purpose if they can operate without a direct and permanent tether. As such, many devices rely on portable sources of power in which energy is stored for future use—the most common of which is the battery. The smartphone for example, can only function as a portable communications and entertainment device because it is built with an internal power supply. Many other devices rely on batteries as well, including cars (especially hybrid and all-electric cars), laptops, and tablets [1]. If any of these technologies were constructed without batteries, they would require constant access to the power grid, and thus would be limited in their range of movement and use. Because so many devices are reliant upon batteries, the capabilities of our technology are dependent upon the quality and capability of batteries. However, while batteries enable many different technologies, they also contribute to some of the hindrances that prevent those technologies from progressing at a faster rate. Significant advances have been made in battery performance, but they still have not reached a level that makes certain innovations viable.

The current, most widely-used battery is the lithium ion (Li-ion) battery. These work by transferring positively charged lithium ions between the two electrodes of a battery. When charged, the ions are contained in the negative electrode, or anode. Upon use, as the battery converts the chemical energy it has stored into electrical energy, the ions travel to the opposite electrode (the positive cathode), creating a current and thus transferring change and electricity. While being charged, the process happens in reverse, with electric energy being transferred to chemical as the lithium ions travel back to the original electrode. Figure 1 below illustrates this process, showing the transfer of lithium ions back and forth between the two electrodes.

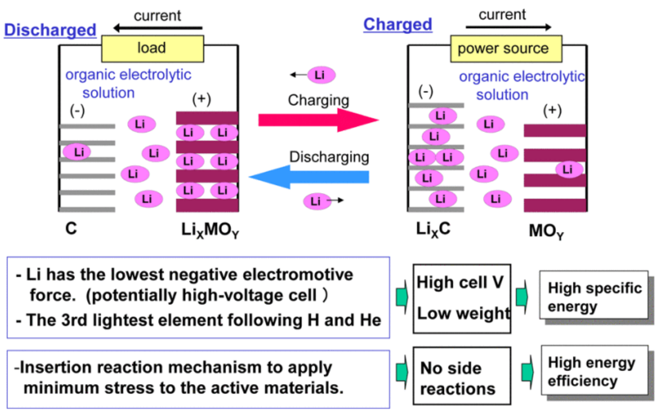


**FIGURE 1 [2]**
**Design of Lithium-ion batteries**

Lithium ion batteries, with high specific energy, single-cell voltage, energy efficiency, and long life spans, are excellent sources of power [2]. However, while they are the most efficient rechargeable battery available commercially and operate at low costs at $150 per kilowatt-hour (kWh), this still exceeds the $100 kWh goal for affordability set by the US Department of Energy [3]. Even with a specific energy and energy density more than three times that of the next best battery, the silver-zinc (Ag-Zn) battery, the lithium-ion battery still cannot provide enough power for some things [4].

For example, due to a variety of environmental factors, including climate change and finite fossil fuel supplies, people have turned to the development of electric and hybrid vehicles to reduce emissions and fossil fuel dependence. Lithium-ion batteries have become the main power storage system for these vehicles but are still unable to match the performance of a vehicle driven by internal combustion engines. In a paper on storing energy in batteries, Dr. K.M. Abraham states that "Energy densities of Li ion batteries, limited by the capacities of cathode materials, must increase by a factor of 2 or more to give all-electric automobiles a 300-mile driving range on a single charge" [4]. For electric and hybrid vehicles to become widespread, they must first meet, or at least near, the capabilities of the combustion engine. In order to improve their performance, improvements must first be made to their power supply—the battery.

Similar issues are faced in other sectors that rely on powerful batteries to function properly, one of the most prominent being the personal electronics industry. As personal electronic devices have become faster and more functional, they too have begun to reach a point where current lithium ion batteries can no longer support them at peak efficiency. This is demonstrated prominently in smartphones. As they become more advanced, they begin to ask more of their power supplies. Battery life thus becomes a major concern, with each generation of phone typically offering a slightly better battery than the last to address this issue. However, this usually comes with the downside of a slightly bigger battery and thus a bulkier phone.

In addition to the limited capabilities of lithium ion batteries, there are other factors that demonstrate the need for new battery designs. Some variations of the Li-ion battery make use of materials with increasingly finite supplies, which will have an adverse effect on the price and availability of batteries in the future [3],[5],[6]. Additionally, the depletion of these resources could lead to shortcomings in other areas as well. Some of these same variations, due to procedures used during the processing and production of their constituent materials, also impact the environment and human health negatively [5],[6]. These drawbacks—the scarcity of resources and resultant economic instability, environmental and health hazards, and limiting properties—present issues that must be solved or minimized to the point of being negligible.

Ultimately, lithium ion batteries in their current manifestation cannot continue as our primary means of portable energy storage—they are not a sustainable solution. The current use of rare materials in lithium ion batteries alone is in direct violation of the most basic definition of sustainability—the preservation of resources for future generations. However, lithium ion batteries also violate other aspects of sustainability. Among the United Nations' 17 goals for the development of a sustainable world are good health and well-being, economic growth, industry and innovation, responsible consumption and production, and climate action [7]. Presently, the use of lithium ion batteries seems contrary to these goals: the toxicity of the processes used to produce the raw materials that make them up are harmful to both the environment and human health, while their rarity is in violation of the idea of responsible production. As they are depleted, the resulting economic instability would lead to economic downturn rather than growth. Finally, the limitations of Li-ion batteries are a hindrance to the development of industry and further innovation in many fields.

### A Possible Solution

As it has become clear that our current batteries are not long-term solutions, researchers have begun to turn to alternatives. Since the shortcomings lie in the chemistry of the battery, new and novel materials that could be used in composites to increase the efficiency of specific components or in completely new battery designs have become a focus. One such material is graphene, which although theorized for many years, was discovered only recently. It has been shown to possess remarkable qualities due to a unique structure that increases its surface area and conductivity—as well as other properties. Although still not fully understood, many have begun to test graphene in electronic and energy systems, where the material has demonstrated that it can greatly improve efficiency. Additionally, graphene seems to be able to address the issues with sustainability currently inherent in lithium ion batteries.

While functionality is important, the vital role batteries play in our society makes it imperative that they represent a sustainable technology as well. Graphene, in addition to displaying desirable characteristics, also seems to solve the issues with sustainability. However, it also has its own considerations. The demand for batteries specifically necessitates economic sustainability, in which we include the ideas of responsible consumption and production, economic growth, and promotion of industry. As such, we will discuss graphene batteries in the context of the ability to mass produce graphene to meet demand, as this will determine the economic stability of the industry and whether they can become a viable alternative. Additionally, we will evaluate the potential for graphene and graphene-enhanced batteries (GEB's) to minimize the environmental and human health concerns associated with the manufacturing of some lithium ion batteries. Ultimately however, the focus for sustainability will be on how batteries that incorporate graphene will enable and foster innovation, as this is where current lithium ion batteries have begun to fail.

## GRAPHENE AS AN ALTERNATIVE COMPONENT IN BATTERIES

### Material Properties of Graphene

Since its isolation in 2004—the first time its properties were observed [8]—graphene has been a material of great interest. It is unique, featuring a structure that has contributed to many desirable characteristics. As a direct result of these properties, graphene holds great potential in a variety of applications across myriad sectors. It is its structure and the properties that result from this structure that has led many researchers to attempt to incorporate graphene into numerous electrical and energy systems, of which batteries are one of the most prominent applications.

Graphene is an allotrope or one of various physical forms, of carbon, along with other materials like diamond, coal and graphite [9]. Specifically, it is a two-dimensional sheet of carbon atoms, arranged in a honeycomb-lattice or hexagonal structure [8]. This characteristic structure arises from the $sp^2$ hybridization of its carbon atoms, which creates a trigonal planar geometry where each carbon atom is bonded to three others [10] as pictured in Figure 1. Its two-dimensional structure, combined with its geometry and resultant hexagonal pattern has lent itself to structural flexibility, as well as numerous other desirable mechanical and electrical qualities. Additionally, graphene forms the basis to other materials with several remarkable qualities as well, including carbon nanotubes and the more common graphite. Figure 3 shows how the two-dimensional arrangement of graphene is manipulated into various other forms.

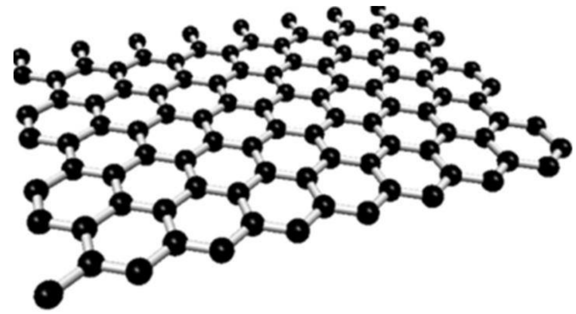

**FIGURE 2 [11]**
**Graphene's 2D Hexagonal Lattice**

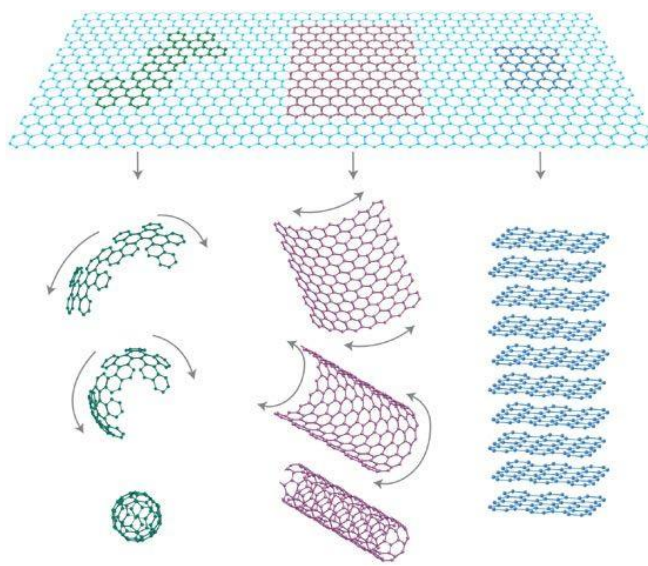

**FIGURE 3 [12]**
**Graphene in various shapes and forms**

In order to determine the extent of these properties, extensive research has been done on the material. Roham Rafiee and Amirali Eskandariyun conducted a comparative study on the Young's modulus of graphene, a quality defined by Encylopaedia Britannica as "a measure of the ability of a material to withstand changes in length when under lengthwise tension or compression" [13]. In this study, they used a continuum model based on Elastic theory to simulate graphene and analytically determine the elastic modulus of graphene. It was concluded that the material possessed a Young's Modulus upwards of 1.0 terapascals

(TPa), averaging at about 1.261 TPa [14]. Now this is only one measure of the strength of a material, but other studies have shown similar values for varying strength measurements. One of the most important is intrinsic strength, the maximum stress a defect-free material can handle before failing. James Hone, in a study into the elastic and intrinsic strength of graphene, determined that with a Young's Modulus of 1.0 terapascals, third order elasticity of -2.0 terapascals, and intrinsic strength of 130 gigapascals for bulk graphite, graphene is the "strongest material ever measured" [15].

The strength of graphene largely results from its two-dimensional structure. Aron Griffith, in his article "VI. The phenomena of rupture and flow in solids" theorized that the breaking strength observed in a brittle material is determined by the flaws in that material, not by the strength of the atomic bonds. He emphasizes that "in the limit, in fact, a fiber consisting of a single line of molecules must possess the theoretical molecular tensile strength," which suggests that single, one dimensional lines of molecules, would display the intrinsic strength—the greatest strength available to a material—because they would be entirely free from defects [15],[16]. Similarly, graphene displays a high intrinsic strength. Although graphene can have defects, its two-dimensional lattice largely minimizes them, and thus it will often express a strength close to that of its intrinsic strength.

However, graphene's two-dimensional structure has contributed to qualities beyond strength that make it appealing to the energy field, and more specifically in this case—batteries. One characteristic of interest is its large theoretical specific surface area (SSA) of approximately 2630 square meters per gram ($m^2/g$) [17]. This quantity, the ratio of surface area per gram of substance, is particularly important to potential battery components, as it allows them to store and release charge carriers—vital to any component dealing with energy storage [18]. The more charge carriers (like Li ions) the material can store and release, the greater the storage and rate of energy transfer. Additionally,
single-layer graphene has been found to have a conductivity several orders of magnitude higher than that of graphite, a material commonly used in the typical lithium ion battery [11]. The $sp^2$ hybridization of graphene's carbons result in the formation of half-filled pi ($\pi$) perpendicular to the plane of the material. The particles in these bonds, Dirac Fermions or massless electrons, display an extremely high carrier mobility. Carrier mobility is the ratio of the velocity of the charge carriers in a material to the electric field applied over the material. Conductivity, a material's ability to convey charge, is directly proportional to the mobility. Therefore, the higher the carrier mobility, the higher the conductivity, which allows for the rapid movement of charge across the material [19]. The Dirac electrons s in graphene, with a carrier mobility near the speed of light, suggests high conductivity [11]. This, combined with graphene's large surface-area to mass ratio, suggests that it will be able to carry out the tasks of storing and conducting charge that define batteries.

Interestingly, graphene can also be used to introduce desirable traits in composite materials or in conjunction with other structures and processes to enhance functionality. A study conducted by Rongrong Jiang, Xufeng Zhou, and Zhaoping Liu, highlights this possibility. In their experiment, they tested the change in strength of copper with the addition of nickel-plated graphene, finding that a certain mixture of the composite material experienced an approximate 12% increase in tensile strength from pure copper, while still maintaining ductility and electrical conductivity close to that of pure copper [20]. This demonstrates that graphene not only possesses these characteristics on its own but can be successfully implemented in composite materials to introduce, amplify, and negate several properties.

Graphene's large number of desirable qualities, along with its ability to be combined into composites suggests that the material could be used in numerous different applications. Particularly, its electrical qualities make it a prime candidate for the enhancement of batteries, especially considering that graphite—a material constituted by layered graphene—is already prevalent in the typical lithium ion battery [2]. Meanwhile, its strength and flexibility lend to practical, everyday use and long-term functionality. Devices with graphene-enhanced batteries rather than the typical graphite or cobalt electrode lithium ion batteries, could see major increases in performance and durability. However, while it seems logical that graphene should become a common feature in portable power sources, there are other factors that must be considered as well.

## Methods to Produce Graphene

In 2004, Andre Geim and Konstantin Novoselov created graphene for the first time using a method called the "Scotch Tape method" [8]. By this process, tape is used to remove layers of graphite (composed of loosely bonded graphene sheets until only a single layer remains—graphene. This method is depicted in Figure 4 below, where a researcher is peeling tape with layers of graphite away from a larger piece. Their discovery had a huge impact, as it that showed graphene--previously only a theoretical substance--could be isolated as a stable material. Additionally, it allowed researchers to, for the first time, identify and measure some of its unique and promising characteristics. However, this method is not that effective; it is incredibly manual, which limits the ability to replicate the process to an extensive scale. As such, researchers have been searching for more efficient methods to create the material.

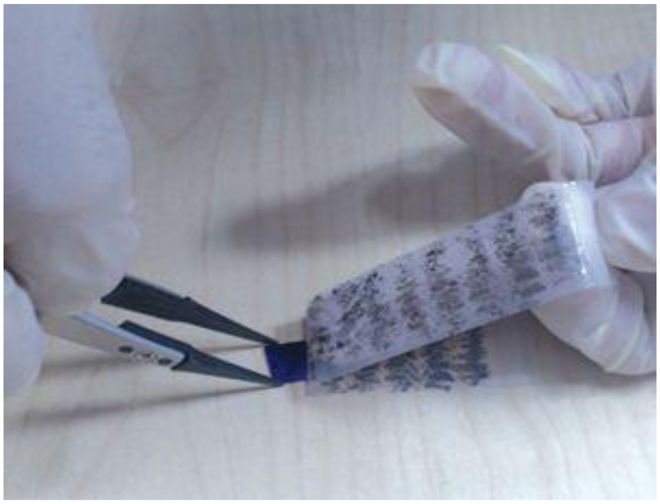

**FIGURE 4 [8]**
**Graphene isolation by "Scotch Tape Method"**

Due to the extensive interest and research in graphene, many ways have been developed to produce it, but one of the most common ways is the "Hummer" method. The "Hummer" method uses chemical reactions to create graphite oxide. This method requires strong oxidizing agents and strong acid to scrape layers off a graphite source. Most involve reacting sodium nitrate and potassium permanganate with concentrated sulfuric acid [8]. However, there is an improved "Hummer" method, discovered by Marcano, that is more efficient and reliable than the original method. First, a mixture of 96% sulfuric acid and 85% phosphoric acid in a 7:3 ratio is reacted with graphite and potassium permanganate. The mixture is then continually stirred for several hours at around fifty degrees Celsius. Afterwards, the hot solution is allowed to cool to room temperature before being poured over ice and hydrogen peroxide. The solution becomes a bright orange color and large particles are removed after series of filtration and centrifugation. The remaining particles are mixed with water, hydrochloric acid, and ethanol. Finally, diethyl ether is added to the mixture and dried under a vacuum with Teflon filter. This creates graphene oxide that will then be put into an acidic water. This separates the individual layers of the graphene oxide to create graphene [21]. However, this comes with an additional cost, present in the materials and chemicals used; the process often includes exposing platinum, nickel, or titanium carbide to ethylene or benzene at high temperatures, which proved dangerous and hazardous to both humans and the environment, which could lead some to question if it's continued use is truly sustainable over time [22].

Another, less proven method of producing graphene has been put forward by Ali Kamara. Through the exfoliation of graphite electrodes in a molten salt (in this case, lithium chloride), they theorize that they can produce graphene nanosheets. The process features only a single step, and makes use of three consumables—graphite electrodes, $H_2$ and electricity. While lithium chloride is used, it is consumed only to a small degree. When a current of 1 A $cm^{-2}$ and an average voltage of 5V is applied to the system, LiCl undergoes electrolysis, decomposing into $Li^+$ and $Cl^-$ in the reaction,

$$Li^+ + e = Li \text{ (at the cathode)}$$
$$Cl^- = e + 1/2Cl_2 \text{ (at the anode)}$$

The chlorine gas then reacts with $H_2$ in the atmosphere above the molten salt, forming HCl [23]:

$$1/2H(g) + 1/2Cl_2\,(g) = [HCl]_{\text{in LiCl}}$$

Then, because HCl is highly soluble in LiCl-based molten salts, it ionizes forming protons($H^+$) and chloride atoms ($Cl^-$). By reduction, the hydrogen ions gain an electron and become hydrogen atoms at the cathode, which in turn may intercalate, or disperse between the layers of the graphite cathode [23],[24]. The formation of high-energy hydrogen molecules between the layers can then result in the exfoliation, or "flaking off" [25], of graphene nanosheets from the graphite cathode [23]. This process is represented in Figure 5 below, showing how the lithium, chloride, and hydrogen react and interact with the graphene cathode to break off graphene nanosheets.

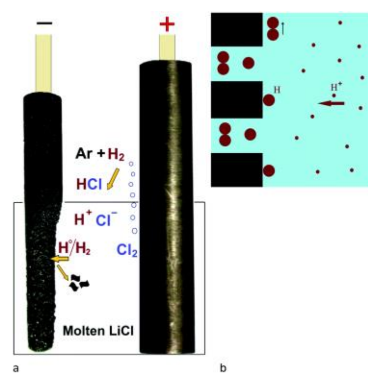


**FIGURE 5 [23]**
**Exfoliation of graphene nanosheets from graphite cathodes**

There are also many other novel ways of producing graphene. Kansas State physicist, Chris Sorensen, has issued a patent for a means of producing graphene in the quantity of grams rather than in milligrams [26]. This simple process shows promise to lead to a method to produce graphene on a far larger scale than ever before.

The process involves filling a chamber with acetylene or ethylene gas, as well as oxygen. Then, a contained detonation is created within the chamber using a vehicle spark plug. The 'soot' from the detonation is graphene and appears as an aerosol gel in the chamber. As Sorensen stated, "Our process has many positive properties, from the economic feasibility, the possibility for large-scale production and the lack of nasty chemicals. What might be the best property of all is that the energy required to make a gram of graphene through our process is much less than other processes because all it takes is a single spark [26]."

Clearly, there are numerous ways to generate graphene, which attests to the flexibility and universality of the substance. However, many of the current methods cannot synthesize the material at a large enough scale to allow it to become commercially prevalent or are simply too harmful to both human health and the environment to warrant their widespread use. But perhaps more theoretical methods like those proposed by Sorenson and Kamali will address these concerns and provide sustainable ways to efficiently produce the material. This will then allow for the widespread, and sustainable use of graphene.

### Economic Viability of Graphene and Graphene-Enhanced Batteries as Replacements for Lithium-Ion Batteries

While graphene has displayed incredible qualities that make it a promising new material in the energy field, there are several other factors that must be considered as well. Perhaps the most prominent of these is the ability for graphene-enhanced batteries to displace our current lithium ion batteries as the incumbent in the portable power industry. This will mainly be based on economic factors, particularly the ability to synthesize high quality graphene at a price that allows for mass production. According to Kamali, "Large scale production of low cost and high-quality graphene from abundant raw materials using eco-friendly methods is a critical step towards the widespread and sustainable use of this so-called 'wonder material'" [23].

Despite the enormous amounts of research conducted on graphene, the mass production of the material remains a recurring problem [8]. As shown previously in this paper, there are numerous methods for producing graphene, but many of them feature one or more flaws that limits their use. This includes: the use or production of toxic or environmentally-harmful chemicals, low output, slow synthesis, and or defective or low-quality product. Additionally, many of these processes do not produce graphene in quantities large enough to be considered commercially viable.

Even though graphene cannot be mass produced at this time, there are considerations with lithium ion batteries that must be accounted for. Perhaps the most pressing issue is the relative rarity of materials used in the electrodes of the lithium ion battery. These electrodes are oftentimes composed of materials like cobalt. Cobalt, which is commonly used in car lithium ion batteries, not only lacks some of the qualities that have made graphene so appealing but is also not sustainably sourced. Most deposits of the mineral are only about 0.003% cobalt, while most economically viable deposits of concentration of 0.1% or more are found in the Democratic Republic of the Congo (DRC)—which was responsible for more than half of the cobalt mined in 2015—and Australia [3],[27]. This dependence on just a few nations for supply means that prices are subject to sudden swings based on factors affecting the economic stability of those nations. Figure 6 shows a graph of the cost per ton of various metals versus their concentrations in ore.

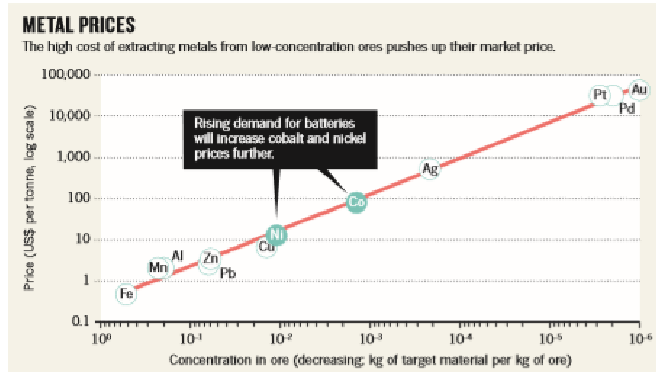


**FIGURE 6 [3]**
**Price per ton vs concentration in ore of common metals**

As the concentration of the metal in its ore decreases, the price of the metal increases. Cobalt, as a relatively rare metal, although not approaching the price of gold and platinum, is significantly more expensive than materials like zinc and copper. Additionally, it is difficult to produce cobalt from its ores, requiring several intensive processes [28]. Cobalt's rarity, as well as the difficulty of extracting it once mined, makes it a relatively expensive material.

In addition to resource depletion, cobalt extraction faces issues with human rights abuses. In the DRC, artisanal miners, who use hand tools to extract ores and include children as young as seven years old are exposed to hazardous conditions without proper safety equipment like respirators. These conditions lead to a variety of chronic illnesses including fatal respiratory conditions. Due to civil strife and other government issues, artisanal miners are unable to work in the DRC's few authorized mining zones and do not enjoy the basic protections that would be afforded by the government. However, many cobalt companies still obtain their supplies from these artisanal miners, encouraging further exploitation [29]. This directly violates the UN's sustainability goals for decent work and good health [7].

Nickel, another material sometimes used in lithium-ion battery electrodes, experiences similar trends. In 2017, 71% of the nickel produced came from Indonesia, the Philippines, Canada, New Caledonia, Russia, and Australia. Although cheaper to extract than cobalt, nickel has experienced an upward trend in prices as well [3].

Ultimately, the scarcity of materials like cobalt and nickel do not allow current versions of lithium ion batteries to serve as long term solutions in energy storage. According to Turcheniuk, "If nothing changes, demand [for cobalt and nickel] will outstrip production within 20 years" [3]. As demand exceeds production, prices for these vital materials will continue to climb, making lithium ion batteries expensive to produce, thus limiting the ability of some of their applications to become widespread—even if other flaws are addressed.

This gives some opportunity for graphene to serve as a replacement for current cathode materials. Although the mass production of graphene is currently unrealized, various methods have been developed that could theoretically produce large quantities of reliable graphene. The method put forth by Kamali for instance, is supposedly eco-friendly, and capable of producing high-quality graphene at a low cost. The process is supposedly quite efficient, able to yield approximately 4.5 kilograms of graphene nanosheets per 10 liters of solution per day. Additionally, even though the mechanism takes place at around 800˚C to increase the hydrogen atoms diffusion constant and allow them to intercalate into the graphite, because it only consumes graphite and $H_2$, the process results in graphene that is relatively cheap. The estimated price to produce graphene by this method ranges from 10 to 20 USD per kilogram, which is comparable to prices for nickel and cobalt at about 14 USD per kilogram and 23 USD per kilogram [3],[23].

This method of production addresses several of the issues of economic sustainability associated with batteries. Primarily, if Kamali's estimations of cost of production are accurate, this proposed mechanism could very well allow graphene to become a widespread, sustainable component in batteries. The ability to mass produce the material makes it relatively cheap and accessible, which will encourage further use and development and drive prices even lower. The process, since it consumes very little, presents little threat of resources depletion. Whereas the price of cobalt and nickel—subject to large swings—will continue to climb as reserves are depleted, the price to produce graphene will remain fairly consistent and potentially decrease as methods are improved. Additionally, the materials are environmentally friendly, thus preserving environmental health. Finally, unlike with cobalt, the materials are readily accessible across the world, and thus do not promote exploitative business practices that take advantage of the economic situations of nations like the DRC.

While this is not the only method being explored to produce large quantities of graphene at a reasonable price, it does demonstrate that graphene can potentially be synthesized at a scale large enough to support widespread commercial use and economic stability in its market. By potentially solving the major roadblock of mass production of graphene, methods like this one point to the potential sustainability of graphene use in everyday life and enable t proliferation of graphene-enhanced batteries.

## Variations and Characteristics of Graphene Batteries

Despite the dubious nature of mass production of graphene, researchers have continued to develop various technologies that make use of the material. While some are centered around graphene as a primary component, others simply use graphene as an additive to increase the efficiency of systems, introduce certain traits, and bolster pre-existing ones. This is especially true for GEB's and energy storage solutions, where innumerable designs have been conceived since researchers were first able to determine the carbon allotrope's properties in 2004. Many of these batteries offer improvements in the energy they can store, the power they can deliver, or both. These values, typically described in terms of specific energy density or energy density, and specific power density and power density, respectively, are indicators of a battery's performance and potential applications.

Perhaps the most common application for graphene in batteries has been as a material for the anode. One design created by Jusef Hassoun and Francesco Bonaccorso to address Li-ion batteries' concerns in cost, safety, charge rate, and energy density, utilizes a copper-supported graphene nanoflakes anode and a lithium iron phosphate cathode [30]. This battery showed promising results, with the graphene nanoflake anode demonstrating a capacity of approximately 1500 mAh $g^{-1}$ compared to the capacity of a graphite anode of about 370 mAh $g^{-1}$. Additionally, the battery was able to achieve a practical specific energy density of about 190 Wh $kg^{-1}$, a value comparable to that of current lithium-based batteries [30]. The quadrupling of the capacity of the anode suggests promising improvements in battery technology. However, the battery was only able to reach a comparable specific energy density to current battery technologies—considering that energy density is one of the primary shortcomings of current battery systems preventing them from expanding into new fields [30], other designs and innovations might prove to be better alternatives.

Another design, perhaps less popular but still demonstrating enhanced performance, is the all-graphene-battery. One version, developed by Haegyoem Kim, features a functionalized graphene cathode and a reduced graphene oxide anode—created through a modified version of the Hummer method—that interact with the lithium ions as shown in Figure 7.

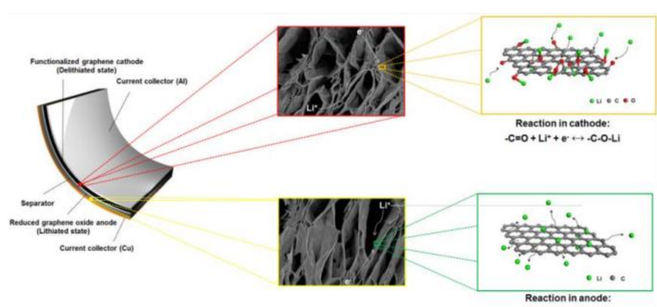

**FIGURE 7 [31]**
**Reactions of lithium ions with electrodes.**

At the cathode, the lithium ions undergo reduction, bonding with the carbon and oxygen complex present there, while at the anode, the lithium in the $LiC_3$ molecule undergoes oxidation, resulting in lithium ions and electrons that then create current flow [31].

This battery, possessing electrodes that are remarkably similar in composition and microstructure was able to avoid power imbalances common in other lithium ion batteries. As a result, its electrodes could operate at maximum efficiency, thus allowing the all-graphene-battery to deliver a power density of 2,150 W $kg^{-1}_{total\ electrode}$ and an energy density of 130 Wh $kg^{-1}_{total\ electrode}$ [31]. According to Kim and colleagues, these values position the battery's "performance in a region inaccessible to [Li-ion batteries] and supercapacitors" [31]. Although a less popular design, this concept seems to display superior capabilities to lithium ion batteries and supercapacitors—systems similar to both capacitors and rechargeable batteries which typically have higher energy densities but lower power densities than batteries. The all-graphene battery is able to both store and deliver energy in large amounts. Kim, along with Kisuk Kang, has developed another system with similar improvements—a hybrid-supercapacitor using graphene wrapped $Li_4Ti_5O_{12}$. While this design does not match the overall performance of the all-graphene battery, it still better balances the tradeoff between energy density and power density [32]. While the second design does not demonstrate levels of performance necessary for widespread use, the all-graphene-battery addresses the shortcomings of both lithium ion batteries and supercapacitors. This bridging between the two types of energy storage systems makes the all-graphene-battery a viable technology, considering its ability to meet or exceed the capabilities of the current lithium ion battery [31].

Finally, a third design addresses some of the chemical problems that prevent Li-ion batteries from operating at peak efficiency. The lithium electrolyte solution contained within Li-ion batteries, if not properly addressed, will begin to form filaments or dendrite that affects the overall life, durability and functionality of the battery. This prevents certain lithium-batteries batteries from using utilize lithium electrodes at a practical scale, even though they would provide the best possible capacity. Jiaxing Huang and Jiayan Luo to address this issue, turned to graphene balls. These materials, resembling microscopic crumpled paper balls, were first created by Haung by allowing water droplets dispersed with graphene nanosheets to evaporate. The resulting capillary action then caused the graphene sheets to crumple in on themselves. These graphene balls, when dispersed within a battery, create a scaffold that prevents the formation of dendrite [33],[34]. Additionally, because the balls are conductive, highly porous, lithiophilic (lithium-loving), distribute rather uniformly and have a high, scalable, surface area, they act almost as a continuous solid through which the lithium ions can travel [33],[34]. From their tests, they concluded that graphene ball scaffolding either drastically reduced or eliminated the formation of dendrite within the battery [33]. By eliminating this significant consideration, Haung and Luo enabled batteries to make use of the best material for their anodes—lithium. But this effect is only realizable to the most practical degree with the addition of graphene as a material.

These three versions of graphene energy storage systems, even though they are not used on a wide scale and are thus far more theoretical in application than practical, demonstrate how graphene has the potential to enhance batteries. They provide several possible paths that graphene-enhanced energy storage solutions can follow, dependent upon the qualities desired in the battery. This 2D material seems particularly flexible in its application, while also promising to enhance whatever system it is incorporated in to.

## SAMSUNG'S "GRAPHENE BALL" BATTERY AND ITS PROPOSED ROLE

Up to this point, we have only discussed theoretical uses for graphene batteries and its possible effects upon the world if it were to become widely used. However, there are modern applications of the battery in development; most notably, Samsung's graphene ball battery. This new battery, utilizing their graphene ball material for both the anode protective layer and cathode materials in lithium-ion batteries, shows serious improvements over their previous batteries. The new technology boasts a 45% increase in capacity, as well as a charging speed five times faster than older models due to the efficient structure of graphene allowing the rapid travel of electricity across its surface. According to Samsung Newsroom, the battery "provides promise for the next generation secondary battery market, particularly related to mobile devices and electric vehicles" [35]. Considering Samsung's recent trends, this advancement would likely be seen greatly in the smartphone industry, and as stated by the Samsung Advanced Institute of Technology, the battery is able to maintain a stable temperature of 60 degrees Celsius, which makes it ideal for use in electric vehicles [35]. This fact may also make the battery a possibility for future models of Tesla's electric cars.

Additionally, Samsung has also "discovered a mechanism to mass synthesize graphene into a 3D form like popcorn using affordable silica ($SiO_2$)" [36]. The synthesis of these "graphene balls", is completed through a chemical vapor deposition process, in which silica ($SiO_2$) particles were fed methane gas ($CH_4$) at a temperature of 1000 degrees Celsius [36]. The resulting material is shown at a microscopic scale in Figure 8, below.

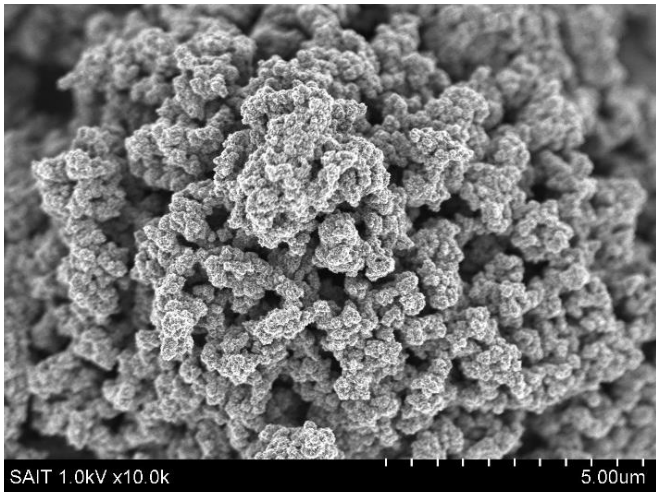


**FIGURE 8 [36]**
**Graphene Ball Material Used in Samsung's Battery**

By synthesizing large quantities of the material, this will enable Samsung to maintain low prices for both the graphene and the batteries in comparison to other models. This is a great step for the future of graphene, displaying its promise for practical use in industry, which may bring other companies to follow in Samsung's footsteps and adopt this new battery. Specifically, due to the benefits of the graphene ball battery's capacity, charge time, and stable temperature, it seems likely that the smartphone, electric vehicle, and other mobile electronic industries will soon switch to a battery like Samsung's.

Although this battery is not yet commercially available, Samsung's planned use of the battery demonstrates that graphene-based batteries do have commercial applications and are not impractical innovations. It is not only more effective than other potential models for graphene batteries in terms of both capacity and charge time, but also less expensive and capable of mass production. As a leading business in the technology industry, Samsung's use of the battery could serve as a catalyst for other companies to follow suit in adopting and further developing graphene-based energy storage solutions.

## POTENTIAL FOR EXPANSION BEYOND THE PORTABLE ELECTRONICS INDUSTRY

With the capabilities of graphene-based batteries, and the creation and possible uses for the graphene ball battery, there is hope that this will become the new trend for batteries within the portable electronics industry; increasing the life of our smartphones five-fold and allowing us to charge them significantly faster than we could with lithium ion batteries [35]. However, with the new possibilities that arise with the introduction of these batteries, many other possible uses for it arise as well.

The limitations of lithium ion batteries, as discussed previously, are halting the expansion of many industries. Industries like space exploration, electric vehicles, biomedical implants, and countless others rely on batteries in order to function, and with the current state of lithium ion batteries are unable to innovate as much as they could due to energy limitations. With the introduction of graphene batteries, this may all change; they have the capability to have applications in many different areas. With graphene's special properties, such as its ultra-high capacity and efficient structure, it enables a functionality previously unseen—blurring the line between batteries and supercapacitors [31]. Implementing graphene batteries could push technological advancement to places we have never seen before, enabling devices to both last longer, and perform more efficiently and effectively. Its minimal environmental and technological drawbacks also show great promise for its sustainability in industry.

One future application that seems likely is the use of graphene batteries in electric cars, specifically Tesla. Due to the increased capacity, charge time, and stable battery temperature, this battery could allow the company's electric vehicles to become far more commercially viable [35]. Tesla currently powers its electric cars with a large lithium ion cell which, although it allows the car to travel fairly long distances off a single charge, they still do not perform well enough for many consumers to to justify purchasing one over a gas-fueled vehicle [3]. The implementation of graphene batteries in Tesla may serve as the push that the company needs to convert many drivers to electric vehicles, thanks to the capacity and charge times that graphene batteries boast.

Another future application that graphene batteries may have could lie in biomedical implants, or IMDs (Implantable Medical Devices). According to professionals in the subject (Achraf Ben Amar, Ammar B. Kouki, and Hung Cao), "To ensure proper operation, most IMDs need to rely on a permanent and sufficient power supply, thus numerous power sources for IMDs have been widely investigated in the last decades" [37]. One of the leading issues in powering these devices is the fact that they must be charged wirelessly, which would require the power source to have a large capacity as well as a faster charging time in order to keep up with the constant draw of energy from the battery [37]. Lithium-ion batteries are the primary form of energy storage used in these implants, but in order to create and utilize more complicated biomedical devices, a larger energy draw is required, raising the need for a more powerful battery. As explained previously, graphene batteries (specifically Samsung's graphene ball battery) are significantly more effective than the current options in these attributes. If graphene batteries achieve the commercialization that they have the potential for, this application could mean saving lives.

## CONCLUSION: THE FUTURE OF GRAPHENE AND GRAPHENE-ENHANCED BATTERIES

With the enormous amount of technological advancements in the past few decades, we have reached a new era of more complex, impactful inventions. The increased role of electronics has led to increased demand for batteries. However, this need has raised many issues with the sustainability of the current lithium ion battery. This includes the use of increasingly rare and hard to obtain materials and the human health and environmental concerns that come with their application. Perhaps the most prominent factor, however, is the inability of current battery designs to enable further innovation. As Li-ion batteries approach their theoretical maximum efficiency, new technologies are demanding more of their power supplies. Innovations like electric vehicles, which require several times the power available to them by current batteries to near the performance of cars powered by internal combustion engines, are prevented from achieving ubiquity by the limitations of batteries.

The new material graphene however, with its two-dimensional honeycomb lattice structure, presents a possible solution to these problems. With a large surface-to-mass ratio, it can store more charge carriers than many other substances. Combined with the presence of its Dirac electrons, which display extremely high electron mobility and contribute to excellent conductivity, graphene possesses many desirable electronic properties that could enable it to function well in energy systems. These theories have been quite consistent with tests conducted on graphene and graphene-enhanced batteries so far, including batteries that utilize graphene electrodes, batteries with lithium electrodes that incorporate graphene balls as scaffolding to prevent the buildup of harmful dendrites, or all-graphene batteries that also display the desirable qualities of supercapacitors. These designs address many of the issues present in current lithium ion batteries. They are typically superior electronically, providing greater energy densities, power densities, or both. Additionally, they utilize materials that are for more abundant than the cobalt and other metals typically used in electrodes.

Despite the apparent superiority of graphene-enhanced batteries however, they are still largely in a development phase. As a relatively new discovery, researchers are still struggling to find a way to produce the material to a commercial scale. The foremost methods that do exist, including the "Hummer" method, are either slow or generate toxic biproducts or small amounts of graphene. However, some newer, more theoretical methods like Kamali's exfoliation of graphite electrodes and Sorenson's chemical vapor deposition method are far more efficient, require less resources and energy, and are environmentally friendly and safe. This means that graphene (and thus graphene batteries), could theoretically be produced at a low price without the threat of resource depletion.

Although applications for these batteries are also mostly theoretical currently, Samsung's development of the "graphene ball" battery and accompanying process of production shows that the technology can be used commercially. With increased capacity, decreased charge time, and greater temperature stability, the "graphene ball" battery could greatly improve the quality of many personal electronic devices like smartphones. With backing of a leading organization like Samsung, this could quickly take graphene batteries from limited, research focused use, to widespread use. This would ultimately drive prices of graphene lower, making it more accessible to other technologies like electric vehicles and biomedical implantable devices.

Of course, we are still in the process of fully understanding the properties of graphene. However, research thus far demonstrates that the incorporation of graphene into batteries can be provide an economically-sustainable and environmentally-friendly solution to current lithium ion batteries. While researchers have yet to determine the most effective way to utilize graphene in batteries, the great variety suggests flexibility of application as needed by the technology in question. In this way, graphene batteries can help drive much-needed innovation.

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