Making Net Zero Emissions an Attainable Goal

Introducing graphene-enhanced technologies to the regulated market to mitigate carbon emissions

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WASHINGTON INTERNSHIPS *for* STUDENTS *of* ENGINEERING

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Preface and Acknowledgements

About the WISE Program:

The Washington Internships for Students of Engineering (WISE) program was founded in 1980 through the collaborative efforts of several professional engineering societies to introduce engineering students to issues at the intersection of technology and public policy. The program allows students to interact with federal regulatory agencies, patent law offices, and standardization agencies to develop an understanding of science policy. Throughout the nine-week program, each intern independently researches and writes a paper on a current engineering-related public policy issue relevant to the student's sponsoring society. For more information about the WISE Program, visit www.wise-intern.org.

About the Author:

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Acronyms

AI - Artificial Intelligence
AIM - American Innovation and Manufacturing
CDR - Chemical Data Reporting
CO2 - Carbon Dioxide
DTSC - Department of Toxic Substances Control
EPA - Environmental Protection Agency
ERDC - Engineer Research and Development Center
FDA - Food and Drug Administration
FTC - Federal Trade Commission
GBA - Global Battery Alliance
GRMs - Graphene-related materials
ISO - International Organization for Standardization
kWh - kilowatt hour
MIT - Massachusetts Institute of Technology
MMmt - million metric tons
NIST - National Institute of Standards and Technology
TC - Technical Committee
TSCA - Toxic Substances Control Act

Executive Summary

Ambitious net zero carbon emissions goals have been set by various climate change agencies and government officials, including President Biden. One of the most prominent emissions goals aims to reach net zero carbon emissions globally by 2050. Unfortunately, the United States is not on track to achieving this goal and the United Nations has announced that several nations have fallen short of their carbon emissions agreements. Increases in deadly natural disasters, species extinction, and global temperatures have heightened the pressure facing scientists and policymakers to convince nations to stay on course to reach net zero emissions within the next few decades.

Most carbon dioxide emissions in the United States come from gasoline combustion, making it clear that changes must be made in the energy sector to mitigate this. Recent innovations in the battery industry have shown exciting promise for the future of clean energy, though regulatory barriers must be overcome to fully establish these new technologies. One such technology is the graphene-enhanced lithium-ion battery which has five times the energy density of regular lithium-ion batteries due to the high thermal conductivity of graphene. However, graphene is difficult to produce on a large scale, and many investors and stakeholders have hesitated to participate in the graphene supply chain due to the lack of regulation and health and safety information on graphene. The EPA, along with other standardization organizations, has worked to understand nanomaterials like graphene over the past decade, but they seem to be behind in producing substantial data on the material's properties. Furthermore, current graphene manufacturers have varying ways of classifying and labeling graphene products, creating additional confusion in the marketplace.

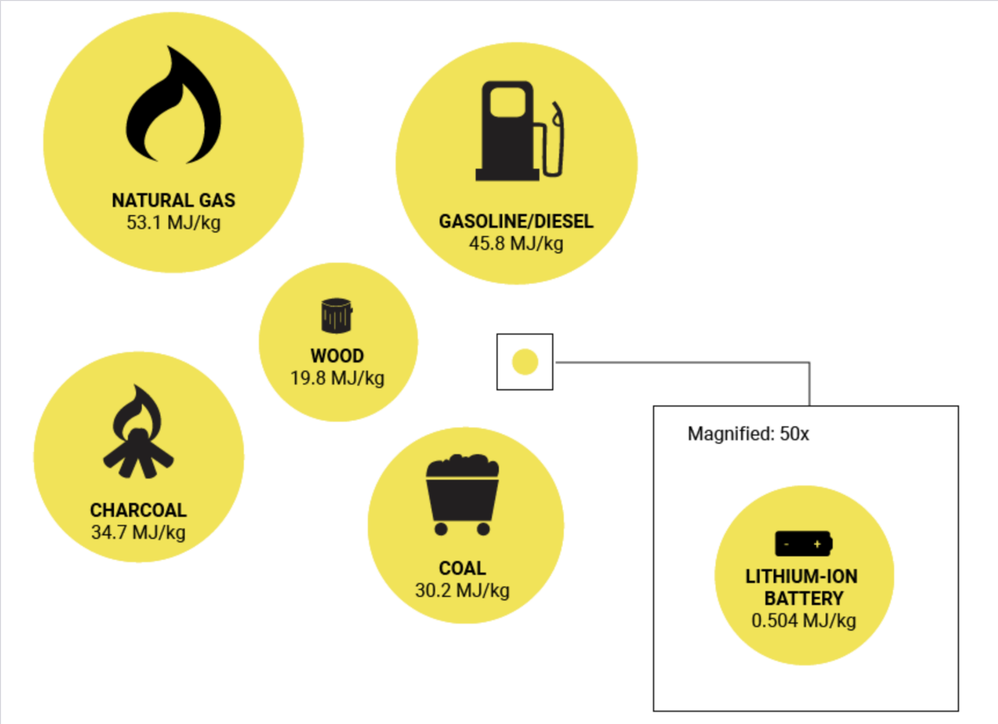
To overcome these barriers and accelerate the process of researching and regulating graphene, I propose that we mandate the EPA's adherence to predetermined deadlines for the creation of regulations for up-and-coming materials, adopt a standardized graphene labeling system, incentivize collaborative research on graphene production methods between universities and federal agencies, and implement a mandatory "battery passport" system to ensure the widespread availability of battery information. These recommendations are aimed at increasing trust and collaboration within the graphene industry and standardizing graphene materials to reduce ambiguity within the supply chain. By implementing these policy changes, we can begin using graphene-enhanced lithium-ion batteries consistently in electric vehicles and grid energy storage systems for higher efficiency. As we improve clean energy alternatives, we can reduce our use of fossil fuels, and thus, decrease overall carbon emissions.

Introduction

As the global climate crisis worsens, energy alternatives will become increasingly critical to reaching the net zero carbon emissions goals set by various agencies internationally. The net zero emissions goals are a set of successive target carbon emission levels that are established to cut greenhouse gas emissions to zero by 2050. These target emissions levels are set to prevent the Earth's temperature from increasing by more than 1.5°C. If the temperature increase of the Earth were to exceed this, our environment could face irreversible consequences including the eradication of coral reefs, an increase in deadly storms, and increased flooding in coastal cities. Historically, the United States has played a large role in exacerbating the global climate crisis. It is among the seven countries that produce the highest rates of carbon emission in the world, despite having a population that is only 4.25% of the world's population [1]. In 2022, the United States emitted a total of 4,964 million metric tons (MMmt) of carbon dioxide (CO2) [2], making up 13.8% of total global emissions [3]. Of the carbon dioxide emitted last year, 1,476 MMmt was produced from gasoline combustion alone [4]. The energy sector plays a fundamental role in the United States' annual CO2 emissions, leading to a focus on finding reliable energy alternatives in recent decades.

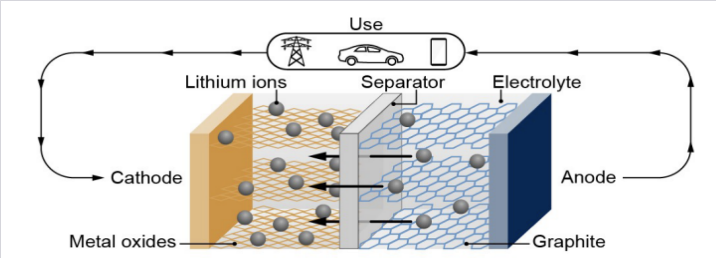
The Biden Administration has made strides toward mitigating climate change by putting a focus on energy-related pollution. At the Major Economies Forum on Energy and Climate, President Joe Biden discussed setting goals to increase the manufacturing and usage of zero-emission vehicles by 2030, decarbonize international shipping, and create carbon-storing technologies [5]. The Department of Energy (DOE) has echoed these sentiments, announcing goals to make renewable energy sources easier to access to deter the use of fossil fuels [6]. Through the American Jobs Plan, the Biden Administration has dedicated a significant amount of resources to the DOE towards this end, particularly towards increasing the scalability of clean energy technologies. A majority of American citizens seem to support the increased actions being taken to reduce carbon emissions, with 54% of U.S. adults describing climate change as a major threat to the country's well-being, and 69% of Americans supporting the prioritization of energy alternatives [7].

Though the future of renewable energy alternatives in the U.S. looks promising, a large barrier to the reduction of fossil fuel use remains. Despite causing record-breaking levels of carbon emissions over the past century, fossil fuels continue to dominate energy generation because of their incomparable energy density. For example, natural gasses produce 53.1 megajoules of energy per kilogram (MJ/kg) while the lithium-ion battery, a popular clean energy storage and emission device used in electric vehicles, produces 0.504 MJ/kg. Thus, a much smaller amount of fossil fuels can produce a greater amount of electricity than batteries, and many other renewable energy sources like wind and solar power. Efficiency is the primary factor in choosing energy sources to power American cities, and fossil fuels have met productivity demands for centuries.



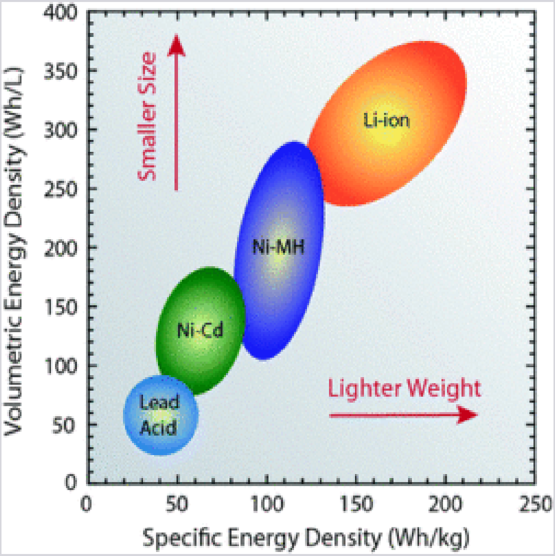
[8] Energy per unit of weight for various energy sources. Graphic from The Brookings Institute.

Despite its current drawbacks when compared to fossil fuels, the lithium-ion battery has been hailed as a promising decarbonized energy source due to its strengths over other battery types, energy storage capabilities, and possible graphene enhancements. First, a lithium-ion battery is an energy storage device made of an anode and cathode that stores lithium, an electrolyte that carries charged lithium ions between the anode and cathode through a separator, and a collector that carries the electrical current.



[9] Diagram of a lithium-ion battery. Graphic from the Government Accountability Office.

Batteries in electric vehicles are less carbon intensive than fossil fuels, contributing to net emission reductions in almost 60 regions around the world over 10 years [10]. Furthermore, lithium-ion batteries have the highest energy densities of all battery technology today, outperforming lead acid batteries, nickel-cadmium batteries, and nickel metal hydride batteries [11]. Lithium-ion batteries also require less maintenance to maintain long battery lives and are not impacted by the “memory effect” unlike its alternative. The memory effect, which mainly impacts nickel-based batteries, causes batteries to remain at lower capacities with partial charging cycles. Lithium batteries have around 300 to 500 charging life cycles and can store energy for grid-scale storage [12].



[13] Specific v.s. volumetric energy density for various battery types. Graphic from the Clean Energy Institute of the University of Washington.

However, the lithium-ion battery faces overheating issues that have led to reported combustion incidents in aircraft. To offset this risk, safety mechanisms must often be added to the battery, increasing its weight and decreasing its energy density. Furthermore, though lithium-ion batteries do not directly emit CO2, the process of harvesting and purifying lithium inevitably results in some CO2 emissions due to diesel machinery used throughout these processes.

By overcoming these deficiencies through modifications to the lithium battery, new energy density and electricity storage opportunities can be unlocked. While fossil fuels have incomparable energy densities, they cannot store energy for future use. Batteries, on the other hand, have gained appeal due to their capacity to store energy for long durations. With increasing energy supply shortages and supply and demand imbalances in the global economy, energy storage solutions may become critical to future technologies. Lithium-ion batteries currently serve as the most common means of energy storage, which is necessary for reliable energy usage from renewable sources like wind and solar energy [14]. When there are low wind gusts and or a lack of sunlight in a certain region for several weeks, stored energy can allow for the continued use of decarbonized sources. Energy storage in batteries allows for energy to be saved and released on demand to deploy clean energy.

Additionally, lithium-ion batteries can collect surplus energy during energy generation periods for prolonged durations.

With the immense potential of lithium-ion batteries in play and the looming irreversible damage at stake with increased carbon emissions and depleting fossil fuels, there has been a focus on enhanced lithium-ion battery technology. Graphene-enhanced lithium-ion batteries are a promising variation of the classic lithium-ion batteries that may come with improved features to increase energy density and storage capabilities even further. Graphene, a form of nanotechnology, consists of extremely thin sheets of five and six-membered carbon rings that can be added to lithium-ion batteries to improve their performance and stability. The nanomaterial's high surface area, chemical stability, and thermal conductivity allow for increased electron mobility in electronic applications [15]. Specifically, graphene forms a 3D electronic conduction network within the lithium-ion battery by boosting electron transport between the electrode and the current collector [16]. This not only increases the energy density of the lithium battery by over 500% but allows for more stability within the electrodes by reducing the internal resistance of the battery [17]. This increase could lead to a battery energy density of around 2.52 MJ/kg. Tesla's brand-new 4680 battery cells have an energy density of around 0.979 MJ/kg, which is less than half of the potential graphene-enhanced lithium-ion battery energy density [18]. Thus, the addition of graphene to lithium-ion batteries can open up completely new possibilities in the clean energy industry, and reduce the incentives that fossil fuel usage offers.

Graphene-enhanced batteries have great potential for the future of clean energy, yet they continue to be overlooked in the automobile industry. A large roadblock in the macroscale usage of graphene batteries is the lack of regulations that exist on the technology. The EPA is behind on regulating newer technologies due to issues with funding, making it difficult for manufacturers to introduce the technology to everyday consumers. Additionally, graphene is difficult to produce and even harder to scale for machinery like car batteries. When modifying graphene for specific applications, defects can form, making it even more difficult to scale the material for larger applications.

Further understanding the setbacks involved in using graphene-enhanced lithium-ion batteries will be critical to overcoming them and creating a viable means of significantly offsetting carbon emissions.

Current fossil fuel investment spending is more than double the amount that can be spent to achieve net zero emissions by 2050 [19]. This also puts the United States' goal of being in line with the 2015 Paris Climate Agreement in jeopardy and exacerbates the already pressing matter of rapid climate change in the 21st century. People are frightened by increasing temperatures, depleting resources, and poor air quality. To drive down fossil fuel use in order to reduce CO_2 emissions, alternative energy sources need to be reliable and as energy-dense as fossil fuels. Graphene-enhanced lithium-ion batteries have this potential, and this needs to be exploited for wide-ranging energy applications.

Background

I. Discovery of Graphene

Researchers began to take a vested interest in graphene and its extensive properties in 2004 when the substance was discovered by Nobel Prize winners Andre Geim and Konstantin Novoselov at the University of Manchester. Taking inspiration from carbon nanotubes, Geim isolated graphene by using scotch tape to peel off layers on a 3D block of graphite. The 2D sheets of graphene that remained illustrated a capability to carry electrical charges by rearranging its electrons into quasi-particles that move close to the speed of light. Thus, instead of mimicking particle motion in classical mechanics, the electrons within graphene display a more similar motion to particles in large hadron colliders, which are high-energy particle accelerators. The isolated sheets of graphene also show immense strength and flexibility, while simultaneously being the thinnest object ever created. Graphene is one million times thinner than a single human hair, and 200 times stronger than steel [20]. These distinctive properties of graphene have inspired scientists to look at its potential use in silicon chips, LCD screens, and as a filler in plastic materials (much like carbon nanotubes). The European Union moved to invest 1 billion euros for the development of graphene-enhanced technology in 2013 and has invested another 20 million euros specifically for graphene-based sensors and optoelectronics. Being named the “wonder material" of the 21st century, graphene and its potential applications have grown exponentially over the last decade, particularly in the energy sector.

II. Graphite v.s. Graphene

Currently, traditional lithium-ion batteries contain graphite, which is a distinct carbon-containing material that is related to graphene, but not the same as graphene. Graphite was discovered several centuries ago in the 1700s and is commonly used in pencils, ceramics, and aluminum canisters [21]. Graphite is a 3D allotrope of carbon with a crystalline structure, making it brittle, unlike graphene. Instead of having sigma and pi bonds between carbon atoms like graphene, graphite contains carbon atoms bonded covalently [22]. Graphene can be thought of as a single layer of graphite. These atomic differences have significant impacts on the tangible properties of the materials; graphene has twice the electrical conductivity capacity of graphite, but it is much more difficult to harvest graphene. Thus, traditional lithium-ion batteries used in most electric vehicles today contain graphite in the lithium battery anode. By creating graphene-enhanced lithium-ion batteries, the capacity of the batteries can be increased substantially.

III. Regulation and Standardization of Graphene

The earliest graphene-based battery concepts were introduced in the mid-2010s, just a few years following the discovery of graphene. Many new graphene batteries were introduced in China at this time, including one under Dongxu Optoelectronics. More recently, graphene-enhanced battery production is being based in larger American cities, including Boston and Los Angeles, where the Cabot Corporation and tech start-up Nanotech Energy are located, respectively. These organizations have marketed the graphene-enhanced lithium-ion battery as more appealing than the traditional lithium-ion battery based on the former's enhanced safety features and efficiency. Nanotech Energy specifically claims to overcome the safety challenges of traditional lithium batteries with a thermally stable separator and non-flammable electrolyte in the graphene-enhanced alternative [23]. By utilizing a graphene-coating method, the start-up can enhance virtually any substrate to increase its electrochemical performance.

The Cabot Corporation has made similar strides, creating a graphene-based additive for existing lithium-ion batteries. The additive is advertised as a technology that was designed to enhance the critical performance of lithium-ion batteries with low loadings [24]. New variations of graphene-based additives or coatings have continued to crop up as organizations centered around innovations on graphene grow globally. With this, increased regulation and standardization of graphene materials have been sought out.

The Environmental Protection Agency (EPA) has clear regulations on traditional lithium-ion batteries, particularly in relation to battery recycling. For consumers, workers, and transporters, the EPA lists specific steps stakeholders should take to properly discard lithium batteries. Due to their high flammability, the EPA has emphasized the importance of taking the proper precautions when processing and sorting the materials. The batteries also tend to contain trace amounts of other valuable minerals including cobalt, which can be difficult to harvest. Thus, the recycling of batteries can make them a sustainable clean energy alternative. The EPA has cited an increase in lithium-ion battery-fueled fires as a growing concern, spurring the creation of the "Avoid the Spark. Be Battery Safety Smart" campaign [25]. Specifically, they point to an incident in Morris, Illinois, where a mill that was storing 184,000 pounds of lithium batteries caught on fire, resulting in an evacuation of all nearby residents [26]. This incident, which happened in 2021, is just one of the hundreds of lithium battery fires that occur annually in the U.S. [27]. Along with promoting the battery safety campaign created by "Call2Recycle", a nonprofit organization, the EPA has created regulatory systems by working in collaboration with standardizing agencies to collect and report data on new graphene-based materials.

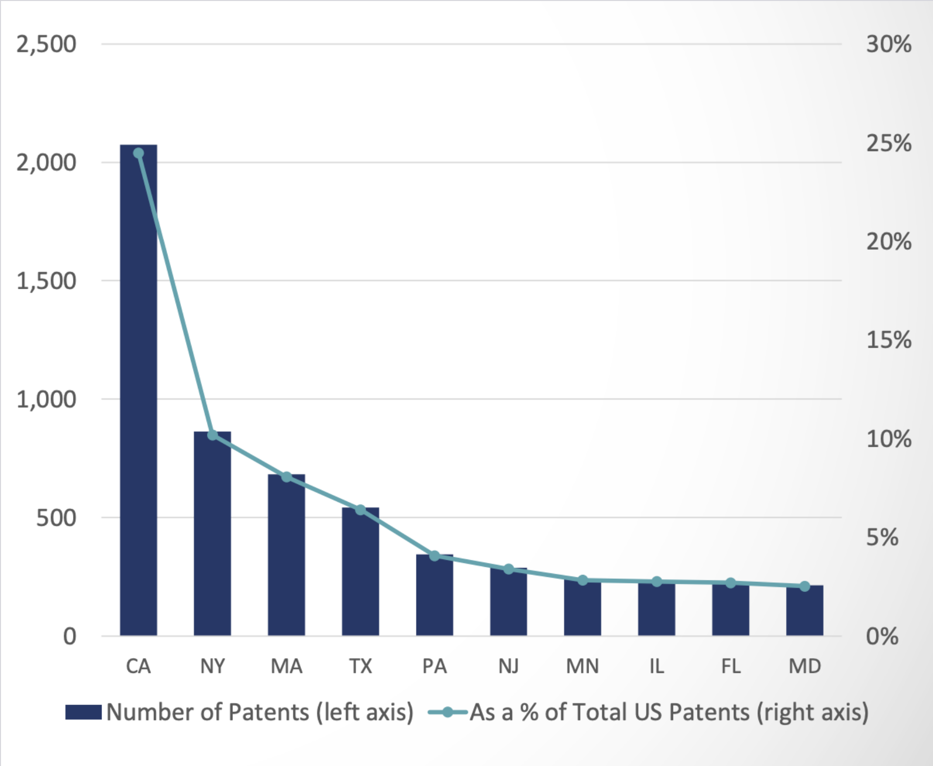
Within its database on battery recycling, the EPA does not mention graphene-enhanced lithium-ion batteries, and only briefly points to the importance of recycling smaller graphite components of traditional battery types. However, in the Chemical Data Reporting (CDR) Database, which is a branch of the EPA that focuses on the reporting, testing, and record-keeping of chemical substances and mixtures, the EPA includes data on graphene, along with various forms of carbon nanomaterials that are currently being or will soon be manufactured. CDR became required under the Toxic Substances Control Act (TSCA) of 1976, which was aimed to regulate the distribution of chemicals that could result in a risk of injury to the health of people and the environment, like lead and mercury. The TSCA was updated in 2016 under President Obama through the Frank R. Lautenberg Chemical Safety for the 21st Century Act to mandate that the EPA evaluate chemicals within specific deadlines and to provide the EPA with a consistent source of funding to ensure they could successfully report data on new substances and protect the public [28].

Though several forms of graphene have recently been reviewed for the CDR list, the data on them is not available to the public as of now due to pending patents. Under the Confidential Business Information's procedural rules, the EPA allows certain chemicals and substances to be reported discreetly to the CDR list for a specified period of time [29]. Representatives at the EPA anticipate that more regulation regarding the use of graphene in new technologies will be created as the chemical continues to gain popularity in the energy sector. The commercial manufacturing of graphene seems to be in its preliminary stages, and research has shown that graphene may cause harmful effects on the human lungs. The uncertainty surrounding graphene-enhanced technology has pushed the EPA to closely monitor the nanotechnology space while noting that graphene does not fit into current testing guidelines for new substances. Specifically, there is no acceptable test for the toxicity of graphene in water columns to understand the material's impact on water pollution.

The EPA often works with other regulatory and standardization agencies to collect information and collaborate with relevant stakeholders. To gain a greater understanding of the environmental aspects of nanomaterials, the EPA works with scientists and policymakers from organizations like, the International Organization for Standardization (ISO), Organization for Economic Cooperation and Development, and the American Society for Testing and Materials [30]. ISO developed a technical committee, TC 229, to create reliable terminology and nomenclature in the nanotechnology space. The EPA is working closely with this committee, which was established in 2005, to develop accurate test methodologies for the environmental impact of nanomaterials and to simulate theoretical health and safety practices regarding graphene [31]. With the Office of Management and Budget, which is the government agency responsible for monitoring budgets surrounding new policies, the EPA conducts interagency reviews to ensure proposed policies are feasible. Finally, the EPA often invites other organizations and government agencies to review their research on new chemicals. The Food and Drug Administration (FDA) is often invited to review the EPA's proposals on waste management strategies.

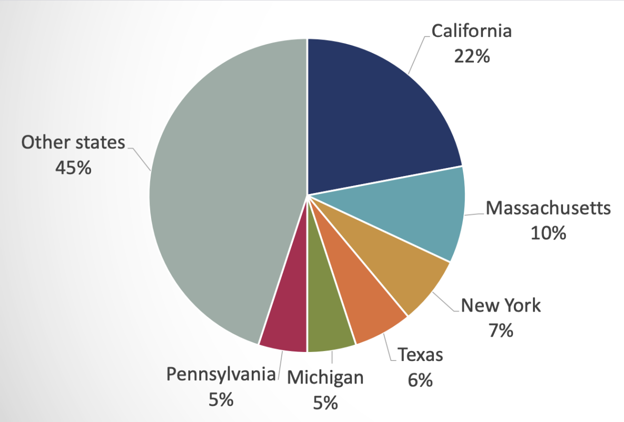
Since the EPA is currently undergoing interagency work regarding the regulation of graphene, the world of nanotechnology remains largely unexplored by governmental agencies. The TSCA will likely define the national use of nanotechnology in the next few years because of its broad reach in the commercial and industrial sphere [32]. The Green Chemistry Initiative headed by California's Department of Toxic Substances Control (DTSC) offers a regional regulatory body in the nanomaterial space. In 2010, DTSC announced its intentions to focus on establishing regulations for emerging nanotechnology through a public workshop on both state and federal nanomaterial policy [33]. Today, the DTSC's website on nanotechnology regulation is archived and access to older reports on nanomaterial company visits and nanomaterials safety information in academic research settings requires the submission of an "Archive Document Request Form" [34]. The DTSC recently released a "refreshed" Strategic Plan for 2020-2024 with no specifics on nanotechnology policy [35].

California is home to one of the fastest-growing nanotechnology industries in the United States, making its regional policies particularly relevant to federal regulations in the space. In 2018, California produced 24% of all U.S. nanotechnology patents, which was more than double the number of patents that New York produced [36].



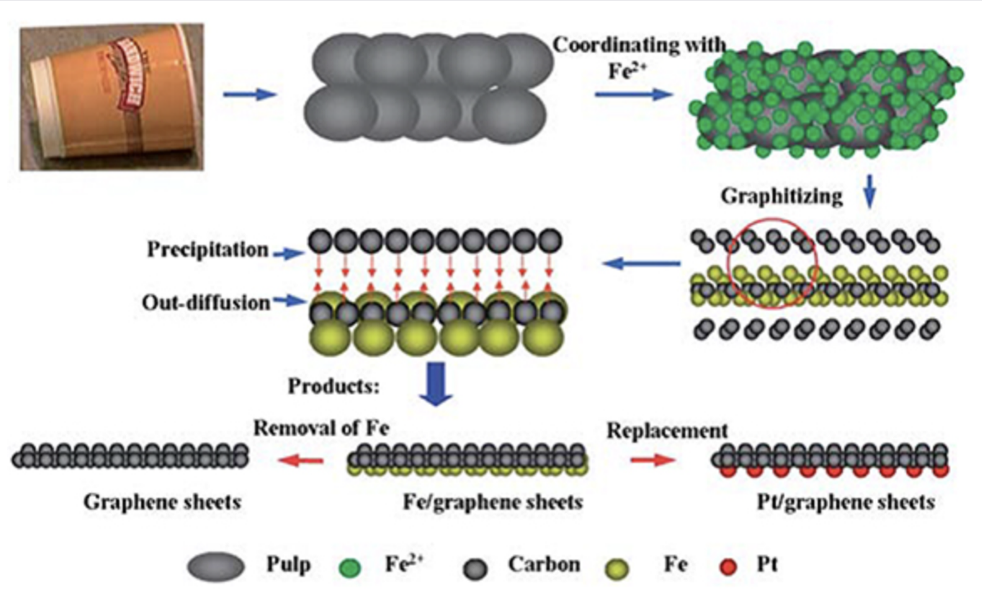
[36] Number of nanotechnology patents per U.S. state as of April 2018. Graphic from American Chemistry Council.

During this period, California was also home to 22% of all U.S. nanotechnology companies.



[36] Percentage of nanotechnology companies in U.S. states as of 2018. Graphic from American Chemistry Council.

It is currently unclear whether California's DTSC, the EPA, or any other federal agencies will propose any graphene-specific regulation for the growing clean energy industry. However, these regulations will become increasingly necessary as new recyclable properties of graphene are discovered. In the last 10 years, primarily in laboratory settings, graphene-related materials (GRMs) have been produced from household waste materials like paper cups, used tea bags, batteries, coconut and almond shells, and coffee. Many of these waste materials are converted into GRMs, which are less-purified materials with very similar properties to graphene, through traditional graphene-producing processes including Hummers' method or the use of a reducing atmosphere through extremely high temperatures and/or the addition of argon.



[37] Diagram of graphene sheet production from a paper cup. Graphic from IOP Science.

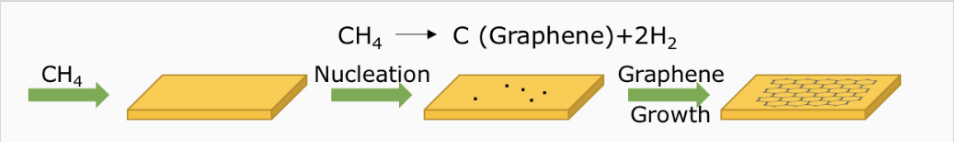
IV. Graphene Production and Sustainability

In late 2021, a team of researchers at the University of Manchester conducted a review of the overall sustainability of the graphene production process. Using a life cycle assessment that considered social, economic, and environmental factors, they found that many of these methods of producing GRMs from graphite-containing waste are largely unsuccessful due to the high amounts of defects in the products [37]. They also found that many of the resulting GRMs lacked 2D morphology due to contamination and oxidation throughout each of the waste-conversion processes. This issue was consistent among each of the starting waste materials, though the starting materials that contained more graphite seemed to produce high-quality GRMs. Thus, despite the potential for harvesting graphene from waste materials, presently, there is no waste-conversion approach that produces GRMs that can be used in real-world applications.

Lithium-ion batteries will make up an estimated 70% of the rechargeable battery market by 2025, meaning lithium supply and other earth-abundant materials will be in much greater demand in the coming decade. This has fueled efforts to both develop modified lithium-ion battery alternatives (like the graphene-enhanced lithium-ion battery) and harvest graphene and lithium from waste products. By continuing these efforts, the U.S. lithium battery industry may be able to sustain itself with little reliance on foreign-produced materials [38].

Following the discovery of graphene in the early 2000s, various methods of graphene production were developed and tested for commercial use. The first method, which was the micro-machine stripping method, came along with the discovery of graphene. It simply consists of using an adhesive to peel off layers of graphene one at a time. This method is clearly not suited to large-scale production, leading researchers to move to more efficient ways of producing graphene.

The chemical vapor deposition method became quite popular because of its cost-effectiveness and its applicability to industrial-level production [39]. It consists of a reaction between methane gas and the surface of a copper metal film in a heated furnace at extraordinarily high temperatures. With fast cooling following the reaction, a layer of graphene forms on the metal plate. The method allows for easy separating, allowing for a shorter processing time in commercial settings.



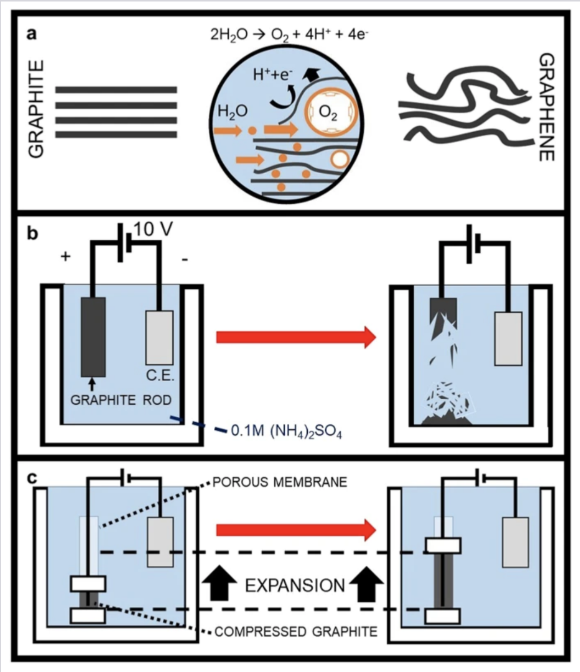
[39] Diagram of chemical vapor deposition method of graphene production. Graphic from ACS Material.

However, the metal substrate used in the reaction must be pure and of high quality to ensure the yield of graphene is high. This adds some cost to the process, making it quite expensive when expanded to large-scale production [40]

The graphite-oxide reduction method offers a three-step process for the production of graphene: oxidation, stripping, and reduction. First, graphite-oxide is created through the addition of potassium permanganate to a graphite and sodium nitrate solution. Then, the newly created graphite oxide undergoes oxidation through high-pressure sonication. This leads to the creation of graphene oxide, which is then thermally reduced to create graphene. Though this method is suitable for both laboratory and large-scale production settings, it is a lengthy process that can take up to a week to complete.

Though initially appealing, the surface epitaxial growth method requires an extensive preparation procedure, resulting in high costs. To create graphene using this method, graphite is heated to around 1000 °C through electron beam bombardment in a vacuum environment. This results in the slow growth of graphene, which is observable by low energy diffraction [40].

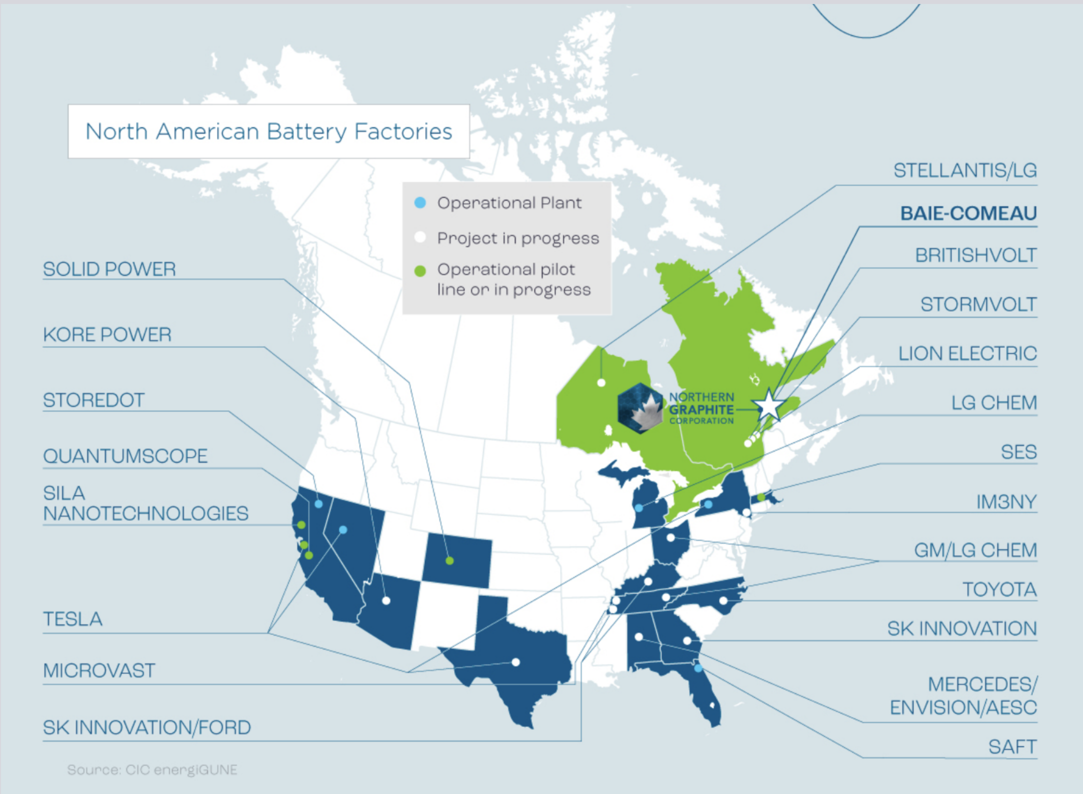
The electrochemical exfoliation method seems to be as highly effective as the surface epitaxial growth method, while also having the greatest potential of all the methods discussed for large-scale production. Graphite is converted to graphene through an applied voltage that pushes ionic species in an electrolyte to increase the interlayer distance within the graphite. This forces adjacent sheets apart, producing graphene. This method produces a high yield of around 65% and is largely stable as long as factors like reactor geometry and electrolyte transport are considered [41].



[41] Diagram of electrochemical exfoliation method of producing graphene. Graphic from Springer Nature.

V. Current State of Graphite and Graphene Supply Chains

Graphite manufacturing and exportation have dominated the global automotive battery supply chain. Since graphene is often produced from graphite, the graphite supply chain has set significant precedents for the potential global manufacturing of graphene. Among all battery types, graphite represents almost half of the weight of the total materials needed for each battery. The average plug-in electric vehicle contains 70 kg of graphite. Natural graphite is extracted from mineral deposits that are mainly found in Turkey, China, and Brazil [42]. As of now, 70% of all graphite, including synthetic graphite which is produced from high-temperature treatment of coal tar, comes from China [42]. China's dominance in the nanotechnology sphere has motivated North American leaders to strengthen the North American graphite supply chain. The Northern Graphite Corporation, founded in 2002, is currently working to build the largest battery anode plant in North America to compete globally and meet the increasing graphite demand.



[43] Map of battery factories in North America as of 2023. Graphic from CIC energiGUNE.

The graphene supply chain is growing rapidly alongside its graphite counterpart. Between 2024 and 2030, the global graphene market is projected to grow from 168 million USD to 609 million USD [44]. In the near future, graphene-enhanced lithium-ion batteries are expected to account for a large market share, particularly in China and South Korea where an increase in patent filings in the space has occurred [44]. However, high production costs and low production volumes remain global barriers to the graphene battery industry.

Ultimately, graphene has many attractive properties that have inspired thousands of researchers to explore its compatibility with current lithium-ion battery technology. The enhanced graphene lithium-ion battery market is still relatively new and the race for market share has already begun. Since graphene can potentially be harvested from food and paper waste, there is an additional incentive to fully pursue the avenue of graphene-enhanced technology in the clean energy sector.

Though it's clear that graphene is becoming a common tool to enhance technology in the energy sector due to its ability to make the technology safer and more efficient, the technology hasn’t reached the mainstream automotive market despite being in existence for almost two decades. Even with billions of dollars in investments, the graphene technology industry seems to be trailing behind traditional lithium batteries and other clean energy alternatives.

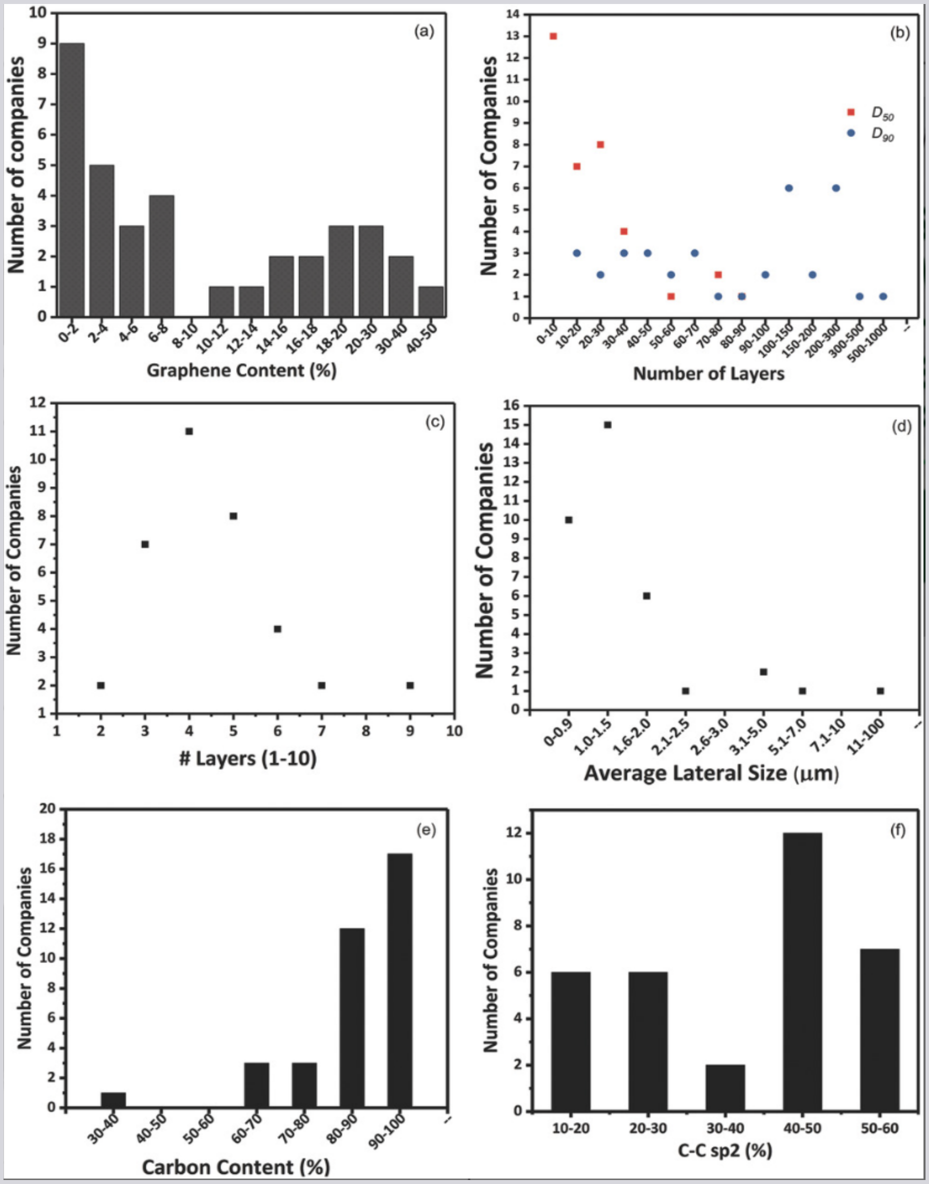
Key Concerns/Findings

I. Disarray in the Current Commercial Graphene Supply Chain

Chemist Derek Lowe describes the current commercial graphene supply chain as an unequivocal "mess" [45]. The primary issue with the national commercial graphene supply is the lack of standardization and distinction between varying graphene products. For example, many items that are labeled as "pure graphene" are actually graphene oxide (GO) or reduced graphene oxide (rGO). These forms of graphene have very different properties that can impact the technologies that are meant to be made from graphene materials. Graphene being mislabeled as rGO is especially dangerous since rGO tends to have many defects that impact its conductive properties. In some cases, what is packaged as "graphene" is simply finely divided graphite particles, and not actually individual 2D layers of graphene. Some manufacturers have taken advantage of the disorganization in this space and simply sell carbon black as a much cheaper alternative than actual graphene.

Furthermore, the graphene that is produced must undergo a stringent quality control process because of its susceptibility to defects. With each layer can come new defects that completely change the overall properties of a batch of graphene. In addition to defects inherent in the batches of graphene produced, more defects in graphene structures can arise when they are modified for specific applications, like for use in graphene-enhanced lithium-ion batteries. Ultimately, the poor quality of a large portion of the graphene that is currently on the market has made it risky for investors and new companies to utilize graphene in new technologies, despite the material's enormous potential. This unreliability has also made pricing graphene difficult and has led to a large range of price points among different manufacturers [45]. These factors have contributed to the bad reputation that the graphene industry has, dissuading potential investors and entrepreneurs in the space from taking risks.

A 2018 study sought to verify the claims that many graphene-producing companies were making about their products. Using the ISO's definition of graphene, a group of researchers from the National University of Singapore conducted tests to provide statistical data on the amount of true graphene in the market. The ISO defines nanomaterials as substances with any dimension in the nanoscale [46]. This definition includes any 2D material, especially graphene which is a single-layered substance. By 2018, hundreds of global companies claimed to manufacture graphene, and many showed large variations in the properties of each batch of graphene [73]. Using a combination of spectroscopy, photoelectron spectrometry, and scanning electron microscopy, the team of researchers found that most classifications of graphene in the industry were erroneous and that some of the "graphene" available was in fact not optimal for many applications. The lack of stringent standards and distinctions between the forms of graphene that work best for particular applications have exacerbated the unreliability of the global graphene industry, stalling any significant progress that can be made. By creating a wider range of graphene categories, standardization agencies, and federal organizations may be able to mitigate the false advertising that happens far too often.



[73]

The main factors resulting in the misnaming of graphene products are the confusion between graphene v.s. bulk graphite, graphene contamination in common manufacturing processes, and the absence of carbon content labels. ISO has defined stacks of graphene with over 10 layers as “bulk graphite”, meaning that the way in which graphene is packaged and shipped can dramatically change its qualifications and properties. Additionally, many manufacturers do not specify the carbon content of graphene samples. Carbon content analyses done in laboratories have revealed that very few companies produce graphene with 100% carbon content and that it is actually more common for these materials to contain less than 50% carbon [73]. The contamination of manufactured graphene often comes from chemicals used throughout the graphene-making progress and can contribute to the lowered carbon content of graphene. The contamination of graphene batches can also impact the number of bonds within the substance, and add sp3 carbon bond defects when graphene should only contain sp2 carbon bonds. These kinds of defects are exacerbated by the presence of transition metals in reactors, and can ultimately reduce the efficiency of batteries created with damaged graphene.

Finally, stronger distinctions in the ways graphene can be used may help with the confusion surrounding the industry. Because different grades of graphene can drastically change the properties of the material, different applications will require different forms of the material. For example, when graphene is used from composite materials (i.e. to reinforce ceramics), large graphene flakes with two to three layers are more suitable [73]. However, for electrodes in neurotechnologies, single-layer flakes of graphene are much more suitable. Thus, commercial suppliers should specify what forms of graphene they are producing to best suit each individual case.

II. The Present and Future of the Graphene Supply Chain

The current graphene supply chain is slowly maturing and trending toward a healthy and diverse supply ecosystem. Manufacturers are continuing to put the most focus on cultivating methods for the production of high-quality graphene at low costs [47]. In light of publicized information on the true distinction between various graphene and graphite products, companies have functionalized graphene in unique ways to transfer the appealing qualities of graphene to new material matrices. The global graphene market is still relatively small, due in part to the untrustworthiness of some graphene manufacturers. High upfront costs of the large-scale production of graphene have deterred some stakeholders from making investments in the space. To achieve a fully functional graphene “ecosystem”, entities such as distributors, companies that specialize in matrix dispersal, product developers, and research institutions must come into play. Printing and coating methods of graphene transfer may also come into consideration as companies grapple with the high costs of producing graphene.

Tesla is rumored to make strides in the graphene industry by releasing a new graphene-enhanced lithium-ion battery that could double the range of Tesla’s Model S car to around 500 miles [48]. However, Tesla’s CEO Elon Musk admits that the cost of the graphene-enhanced battery would make the vehicles markedly more expensive. Starting in 2020, a string of start-up companies have claimed to create graphene batteries with lowered costs, but it is unclear whether this is being done on a scale large enough to sustain the automobile industry.

Engineers at the Massachusetts Institute of Technology (MIT) have also attempted to create a more scalable method for producing graphene by making continuous long strips of the substance, mimicking rolls of aluminum foil or saran wrap [49]. They have worked to optimize this method for filtration membrane purposes by using the chemical vapor deposition method. The continuous element of this new method of producing graphene has made it particularly appealing for large-scale applications. The method entails the use of two spools connected by a conveyor belt over a furnace [49]. The first spool unravels a roll of copper foil when it enters the furnace and is bombarded by methane and hydrogen gas to slowly produce graphene. The researchers have been able to produce graphene at a rate of 5 centimeters per minute, and have produced up to 10 meters of graphene in one session. Researchers also conducted various tests of the method to test its flexibility for different applications. This included testing different ratios of methane and hydrogen gas, different speeds, and different solutions for diffusion. Using these customizations, manufacturers can potentially tune this method of creating graphene to their specific needs. In the future, this continuous method of producing graphene will include fundamental steps, like polymer casting, that have traditionally been done by hand. By making this process truly scalable, trust may be put back into manufacturers, making consumers and investors more confident in participating in the commercialization of graphene [49].

III. Regulation v.s. Innovation

Recent Supreme Court decisions involving the EPA have set precedents that may impact the growth of the graphene industry. A year ago, the Supreme Court ruled in the plaintiff's favor in West Virginia v. Environmental Protection Agency, a case about the powers granted to the EPA under the Clean Air Act of 1970. The act was created to reduce emissions from industrial sources by allowing the EPA to define the most efficient systems of pollution reduction. This has steadily lowered air pollution by reducing mercury emissions by 45% since 1990, reducing the lead content of gasoline, and by reducing the primary pollutants that cause acid rain [50]. However, the conservative-majority Supreme Court ruled in a 6-3 decision that, despite the Clean Air Act, the EPA does not have the authority to direct power plants to shift to cleaner sources of energy like wind and solar [51]. Almost a year later, the Supreme Court diminished the EPA's powers further in Sackett v. Environmental Protection Agency, a case about an individual's right to build on federally protected wetlands. Michael and Chantell Sackett of Idaho began to build a home on wetlands when a neighbor reported their actions to the EPA. On the grounds of the Clean Water Act, which stipulates that individuals and organizations must go through regulatory measures before building on wetlands, the EPA found that the couple was in violation of the act, and ordered them to stop building until they were in compliance with the regulation [52]. In a 5-4 ruling, the Supreme Court not only granted the Sacketts' permission to continue building on the wetlands without the EPA's approval but also adjusted the definition of a federally-protected wetland to be more narrow.

The current Supreme Court seems to be adopting a trend of reducing the powers of the EPA and other federal agencies, contributing to a conflict between regulation and innovation. The graphene battery industry has the potential to strengthen clean sources of energy and reduce emissions, however, with little to no regulation, the industry will remain small and unreliable. Increased regulation of the graphene industry could positively transform it, while still allowing for innovation in the energy sector. The balance between regulation and innovation remains a critical one in American society, and it seems that the graphene sector has not realized its true potential because of the current lack of regulatory action. As the Supreme Court sets new precedents to determine the actions that the EPA can take, the future of the graphene industry will continue to be clarified.

Policy Recommendations

The main issues impacting the full integration of graphene-enhanced technologies in American society include the lack of reliable regulations on the relatively new and unfamiliar technology, the difficulty faced by commercializing graphene products, and the lack of trust within the graphene space due to the mischaracterization of graphene products. To successfully overcome the regulatory and manufacturing barriers preventing graphene-enhanced lithium batteries from being utilized in the energy sector at their full capacity, the following policies should be implemented. The following criteria will be taken into consideration when evaluating the predicted impact of each recommendation:

1. Feasibility
2. Short-term Impact
3. Long-term Impact
4. Estimated cost

Recommendation 1: Mandate EPA adherence to predetermined deadlines for the creation of regulations/quality control practices for new nanomaterials.

The EPA has struggled to keep up with new chemicals and nanomaterials in their CDR inventory, leading to very little regulation on graphene, a nanomaterial that has now existed for almost 20 years. Employees of the EPA have voiced concerns about graphene in the marketplace, largely because of how much is unknown about the substance. There is little data on the long-term environmental impacts of graphene and there is uncertainty surrounding any potential health impacts of graphene. To make progress in answering these fundamental questions on the material and create standard regulations in the graphene space, the EPA must collect and analyze data on new technologies in a timely manner to encourage the development of companies and new inventions surrounding graphene.

The executive and legislative branches have direct power over the EPA. Congress authorizes the EPA's creation and enforcement of chemical and environmental regulation initiatives. Through executive orders, the president can push the EPA to focus on certain technologies or actions. To successfully implement this recommendation, an executive order should be administered to promote the use of graphene-enhanced technology in the renewable energy sector.

Executive Order 13859 can be used as a blueprint to form a new order on the regulation of graphene in the marketplace. The EPA describes Executive Order 13859, titled "Maintaining American Leadership in Artificial Intelligence", as an outline of federal strategies that can be used to set up the United States as a global leader in the artificial intelligence (AI) industry [53]. This order, which was administered in 2019, focused on outcompeting China in the AI industry by mandating that federal agencies allocate some of their budgets to AI research and development, promoting collaboration between academia and the private sector, and promoting fellowships and education grants for academic work in AI. This executive order also focuses on the security risks involved in the growing AI industry and encourages the development of plans to protect American AI technology from strategic competitors. Though the context of Executive Order 13859 does not completely match the history of the graphene industry, its key points could allow us to overcome the regulatory barrier blocking graphene. Primarily, by mandating that federal agencies like the EPA and DOE allocate funding to the research and development of necessary regulations for fast-growing industries, the executive branch can hold them accountable to reasonable timelines and ensure relevant health and safety information is publicized as soon as possible. By getting regulations out faster, new industries can have the proper infrastructure necessary to grow and foster trust among all relevant stakeholders, including private investors who support a significant chunk of the American economy [54].

To uncover the potential of graphene technologies, academic institutions, and private organizations have already started working together. The U.S. Army Engineer Research and Development Center (ERDC) partnered with three universities last year, the University of Mississippi, Jackson State University, and Rice University, to develop graphene application systems. A U.S. military representative who headed this initiative emphasized the potential that collaborations like these have, citing the future of graphene technology application as one that promotes national security and renewable energy [55].

Ultimately, this recommendation is relatively feasible given the current presidential administration's focus on growing the clean energy sector. Since promising data on the renewable energy potential of graphene-enhanced technologies exist, an executive order on establishing graphene regulations could be justified. Though this likely would not result in tangible graphene/nanomaterial regulation immediately given the time designated for the EPA to draw up proposals and request comments, regulations could be developed relatively quickly after the official implementation of the executive order. With clear regulations defining the graphene industry following suit, graphene-based products will have tangible means of entering the broader American market.

The cost of this initiative is difficult to quantify because of the vast range of funding the EPA gets to carry out executive orders. The EPA's proposed fiscal year 2024 budget includes devoting $64.4 million to implement the American Innovation and Manufacturing (AIM) Act, mainly geared towards phasing out specific greenhouse gasses [56]. Since the AIM Act also authorizes the EPA to "facilitate the transition to next-generation technologies through sector-based restrictions", a portion of this proposed funding could be delegated towards another kind of "sector-based restriction" in the nanomaterial space [57].

Recommendation 2: Adopt a standardized, nuanced graphene identification system.

The current organizational structure of graphene labeling in the American marketplace has failed, leading to buyers purchasing diluted or incorrect graphene products, and preventing investors from fully committing to the graphene space. If graphene-enhanced batteries are to be made mainstream, the basic infrastructure of the graphene supply chain must be sound. To accomplish this, a standard labeling practice must be adopted for all graphene-based products. Additionally, penalties should be administered by the Federal Trade Commission's (FTC) Bureau of Consumer Protection Program when companies do not adhere to said labeling practice. Finally, this labeling practice must also require completeness in labeling, which should include the percentage of carbon in each product. Since graphene products are prone to defects within the 2D carbon structure, the percentage of true graphene within a product should be made completely transparent. Along with the percentage of carbon content, graphene product labeling should include the method of graphene production and the optimal application of the graphene, based on the form the material is in.

The FTC has already enacted policies requiring the specific and accurate labeling of products. In 2018, the "Test Procedures and Labeling Standards for Recycled Oil" rule was established, requiring specific "testing procedures and labeling standards for recycled oil" [58]. The rule features critical definitions that clarify the distinction between various forms of oil, including new, processed, recycled, used, and re-refined oil [59]. These definitions naturally guide manufacturers to the required labeling standards, while the testing procedures show manufacturers how to identify each of these oil types within a sample. A similarly structured policy for nanomaterials would create a healthy foundation for the infrastructure of the graphene industry.

This recommendation is quite feasible, given the FTC's history of similar policy implementation. For the 2024 fiscal year, the FTC requested $288,872,000 for the general goal of "protecting consumers'' [60]. The FTC also lists a number of lawsuits and consumer protection initiatives, though the budget for each project is not clear. However, this policy recommendation will have a strong, long-lasting impact on the graphene industry if standard graphene labeling practices are properly enforced by the FTC. Other regulatory bodies, including the EPA, may also play a role in the enforcement of graphene-related standards.

Alternatively, the standardization of nanomaterial labeling could be based on current building codes, which are studied and updated by the National Institute of Standards and Technology (NIST). This year, NIST announced a new building standard specifically catered towards collapse mitigation [61]. NIST routinely aids in the research and development of standards to prevent harm. A similar practice led by NIST or a different standardization agency with enforcement capability will increase overall trust in the graphene supply chain, allowing for the development and success of graphene-based technology.

Recommendation 3: Incentivize research on methods for the mass production of graphene through collaboration and funding from the Department of Defense.

Perhaps the largest barrier to the national use of graphene-enhanced batteries is the lack of viable methods for the mass production of graphene. Large amounts of graphene will be necessary for each individual lithium-ion battery, so a cheap and efficient method of producing graphene is imperative. Though some research institutions have already explored methods of producing graphene on a large scale, namely MIT (as discussed in *The Present and Future of the Graphene Supply Chain*), more work can be done to put a larger national focus on research related to transforming the clean energy industry. The untapped potential of graphene material in the United States is clear, and we can overcome this in the coming years by promoting collaboration between regulatory agencies, universities, and industries with vested interests in the development of graphene production methods. Since both engineering and economic factors have defined the movement of graphene-related discoveries since 2004, agencies with expertise in engineering and economics should contribute to the further development of the material.

To incentivize research on methods for the mass production of graphene through collaboration, government agencies like the Department of Defense (DoD), the EPA, and the ERDC should fund graphene research projects led by undergraduate and graduate institutions to not only accelerate the development of viable graphene production means but introduce students to a growing industry. As more emphasis is put on green technologies in the renewable energy market, this collaborative effort between universities and government agencies could foster interest in younger generations who are exploring the space. The current collaboration between these organizations is limited, only consisting of a few research programs with the Federal Aviation Administration, Federal Highway Administration, Federal Transit Administration, National Science Foundation, Office of the Assistant Secretary for Research and Technology, Small Business Administration, and DOE [62]. Some of these research programs are only partially funded, reducing the speed at which new findings can emerge in new scientific fields.

A possible method of creating a constant stream of collaborative projects in new engineering topics could be the designation of a portion of government agency funds for new areas of research. For example, each year a portion of the EPA's funds could be designated to universities who are doing promising research in new fields related to environmental and chemical safety. If specific goals with deadlines are met by the university, they could receive a second round of funding the following year, until the research project is complete. This would benefit the university by attracting researchers and allowing them to produce numerous publications, and this would benefit the government agency by offloading some of the research work they need to complete as new technologies crop up. Furthermore, as the relationship between research institutions and government agencies develops, each entity should be rewarded with additional funding. A larger governmental organization overseeing the work done between regulatory agencies and universities can enact specific deadlines on projects to maintain maximum efficiency.

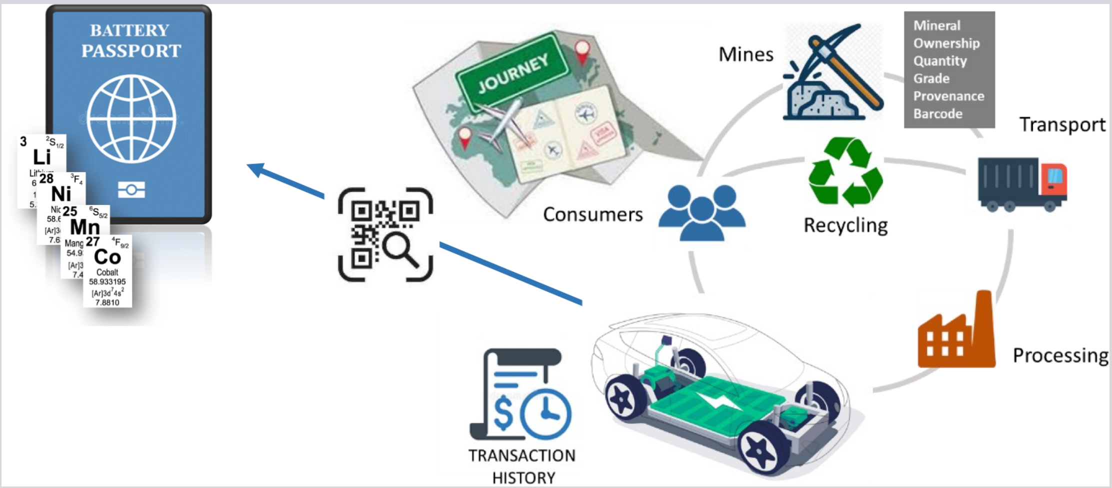
This recommendation will require a large amount of coordination and funding to begin the program. However, if we are to compete with China in graphene technology development, we must take measures to accelerate our understanding of the material. The U.S. is already disadvantaged in the market due to relatively low reserves of graphite. Despite the high initial cost of this recommendation, the long-term impact of consistent collaboration between federal agencies and universities could include the rapid growth of new industries, timely regulation of new materials, and increased innovation due to a more streamlined process to the marketplace.

Recommendation 4: Increase transparency and competitiveness in U.S. battery and graphene industries by requiring a standardized "Battery Passport".

The "Battery Passport'' is a pilot program that was introduced by the Global Battery Alliance (GBA) to facilitate increased supply chain transparency in global battery industries. The passport is a digital record of a single battery's information, including the percentage of recycled components that the battery contains, the origin of the materials used, the estimated amount of carbon emissions from the production of the battery, and the manufacturing history [63]. This information is stored in a QR code on the battery to promote competitiveness in the global battery market, maintain battery supply chain transparency for all relevant stakeholders, create a framework for the benchmarking of batteries when evaluating their sustainability and efficiency, and track overall progress towards sustainability [64]. This program aims to promote long-term competitiveness by making methods of producing batteries from recycled content more transparent, allowing for the development of future generations of lithium-ion batteries.

The GBA has successfully implemented this program in various European countries, and China and Australia have followed suit. The European Union recently announced that in 2026, all electric vehicle batteries over 2 kWh will be required to have a "Battery Passport''. China and Australia have also launched similar programs, but the U.S. has fallen behind the world leaders in battery regulation [65]. Though a few U.S. automobile manufacturers, including Tesla and Ford, have partnered with technology transparency agencies to develop sustainability trackers, there has been no federal effort to standardize a "battery passport". Because of their higher transparency and reliability, foreign battery companies are dominating the market.

The U.S. must enact a federal requirement for a battery passport to increase trustworthiness in the battery supply chain (and in turn, the graphene supply chain) and keep sustainability goals at the forefront. Furthermore, a battery passport could help keep the country in compliance with the Inflation Reduction Act by ensuring that the raw materials used in the battery supply chain are mined, processed, or recycled domestically or in a free trade partner country [65]. U.S. Representatives have already made requests to the federal government for the adoption of a "batter passport" program, with Representative Paul Tonko of New York asking Treasury Secretary Janet Yellen to "in coordination with . . . the Department of Energy and the Environmental Protection Agency, [would] investigate the possibility of creating or adopting a digital battery identifier for use in the U.S. market," [65]. NIST has also advocated for the implementation of digital battery passports to provide electric vehicle suppliers with data to identify challenges and successes within new sustainable technologies in the automotive sector. NIST specifically points out the end-of-life issues that are associated with lithium-ion batteries as a reason behind collecting data on each battery that is produced [66]. Given that NIST has already undergone research on a potential battery passport program, they are well-positioned to collaborate with the EPA to oversee and enforce the program on a federal basis. The ability to track the source and sustainability of materials used in the electric vehicle market will become increasingly critical as recyclable processes are developed and more efficient materials, like graphene, are fully incorporated into the renewable energy space.



[66] Diagram of components that make up the contents of the "Battery Passport". Graphic from National Institute of Standards and Technology.

An American battery passport program is quite feasible, given that a structure for the program already exists in major domestic automobile manufacturers. Furthermore, since the program would allow for data collection immediately, the short-term impact of the program could quickly keep us in line with recent sustainability goals. Though the program will require some initial investment, the data that the program will provide is almost certainly worth it.

Conclusion & Future Directions

The battery has transformed the way we approach sustainability. With further innovation on the lithium-ion battery, we can make the ambitious net-zero emissions goals set by the current administration a reality. Graphene, the wonder material of the 21st century, offers a pathway to do so. However, regulatory barriers continue to leave graphene with untapped potential. To overcome these challenges, a series of policy changes aimed at increasing transparency, competitiveness, and opportunity should be enacted.

The future of renewable energy is an exciting one, particularly when looked at from an energy storage perspective. The lithium-ion battery has undoubtedly changed the way we approach all aspects of green technology, with 77% of electrical storage systems relying on them [67]. The Federal Energy Regulatory Commission, an independent regulatory agency, has started exploring the possibility of electric vehicle-powered houses, which involves the use of energy from lithium-ion battery-powered vehicles to feed the energy grid. This is a large step in the direction of making electricity transfer a two-way street where vehicles can buy and sell energy back into the electric grid. As natural disasters have become more frequent and intense, reliable and efficient energy has become contentious. The future of renewable energy will impact the efficiency of electric vehicles and electric power storage. To position ourselves as leaders in a space that we are already trailing behind in, the U.S. must make serious concentrated efforts towards leveraging the technology and materials already available to us.

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