<u>The Market Dynamics Of Graphene and its Practical Applications</u>

(Economic Impact for Producers and Consumers, Independent Study)

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Abstract:

Graphene is a novel nanomaterial, discovered only recently in 2004. It is also known as a "wonder" material due its vast array of applications in various fields. While there are multiple ways in which graphene can be manufactured, the economics of these methods are not understood nor researched very thoroughly. This paper aims to analyze the market dynamics of graphene manufacturing, via Chemical Vapor Disposition (CVD) and Electrolytic Exfoliation (EE), while also exploring the practical applications of graphene, particularly focused around water filters and Li-ion batteries through the lens of sustainability.

By developing an industrial-scale cost model for graphene manufacturing via CVD and a theoretical cost model for manufacturing via EE, the research shows that graphene obtained via CVD is 60 times more expensive than graphene obtained via EE. While CVD produces better quality graphene today, Electrolytic Exfoliation has immense promise for the future due to its superiority in cost and sustainability.

This paper has immense relevance today due to the sheer lack of economics-centered research on this topic. Using secondary data and interviews with industry experts, the paper offers a comprehensive view into the economic impact of graphene at a large scale.

Introduction:

Graphene is a novel nanomaterial composed entirely of carbon atoms. It is an *allotrope* of carbon. Allotropes are different forms of the same element, owing to different chemical structures (arrangement of atoms). It is obtained from its parent allotrope, graphite, which is what lead in pencils is made of. Graphite is a 3-dimensional entity, consisting of various sheets of graphene, held together by strong intermolecular forces of attraction. Conversely, graphene is a 2-dimensional entity, and exists as a one-atom-thick planar sheet of carbon atoms, arranged in a hexagonal lattice structure. A comparison between the structure of graphene and graphite can be better understood using Fig. 1 below.

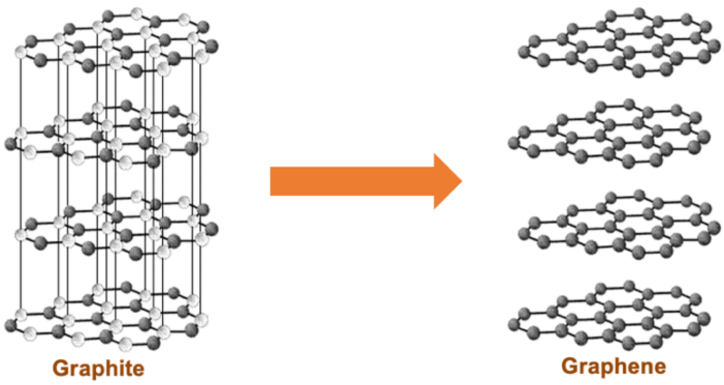

Fig. 1: Graphite vs Graphene

Graphene is an extremely new material, and was discovered only in 2004 by scientists at the university of Manchester (*Graphene: The Wonder Material of the 21st Century | Topics | European Parliament, 2015*). These scientists were Andre Geim and Konstantin Novoselov, who received a Nobel Prize for their discovery in 2010. Since then, research and experimentation surrounding this new material sky-rocketed, and investigations began. Ever since, there have been multiple ways to manufacture graphene, including Chemical Vapor Deposition, Mechanical Exfoliation, Electrolytic Exfoliation, among others.

The nanomaterial quickly proved to be extraordinary, having a wide array of physical properties that allowed it to be used in a variety of different fields, such as electric vehicles, electronic devices, water filters, among others.

Graphene's physical properties include high strength; thermal and electrical conductivity of 3000 W/mK and 3 s/cm respectively; elasticity; and mechanical flexibility (*Graphene Thermal Conductivity - Introduction and Latest News | Graphene-Info, n.d.; O'Neill et al., 2021*). Further, graphene has a high Young's Modulus of around 1,100 GPa and high fracture strength of 130 GPa *Fig. 3 Chart of Young's Modulus as a Function of Density Comparing.,n.d.*). Young's Modulus establishes the relationship between stress acting on a substance and the strain it produces, while fracture strength indicates the maximum weight a material can withstands before it cracks. Further, it is water impermeable and extremely light; one square meter of graphene weighs only 0.77mg (*Admin_Fourmizz, 2023*). In comparison, graphite has considerably lower fracture strength of only 88GPa, Young's Modulus of ~800GPa and a maximum heat conductivity of 2000 W/mK (*Carbon, 2024*). Thus, graphene is classified as a 'wonder material'. It is 200 times stronger than steel and five times lighter than aluminum, differentiating it from the vast set of materials available today.

Aim:

The aim of this paper is to investigate the effect of graphene in the global economy. It will focus on two main aspects – the manufacturing and the practical application of graphene, while also surveying the current graphene market. Specifically, the paper will explore the economics of graphene during its manufacturing via CVD and Electrolytic Exfoliation. It will then explore its economic impact and future potential in the fields of water filtration and Lithium-ion batteries. This comprehensive analysis will weigh the material's pros and cons in a multi-faceted approach, offering unique insights on graphene's future economic impact.

The Graphene Market:

The graphene market has seen significant growth and development in recent years, driven by its unique properties and potential applications across a wide range of industries. According to a report by Fortune

Business Insights, the market was valued at approximately USD 432.7 million in 2023 and is projected to grow from USD 570.3 million in 2024 to USD 5,193.2 million by 2032, exhibiting a CAGR of 31.8% during this period (*Graphene Market Size, Share & Industry Analysis, Fortune Business Insights, 2024*). The largest graphene manufacturer to date is 'Carbon Rivers', with an estimated ClickShare of 41.2% (*11 Graphene Manufacturers in 2024 | Metoree, n.d.*).

The average market price for graphene varies, given its high dependency on the cost of raw materials, technology involved, and production method. However, based on an article published by the Investing News Network (INN), the commercial price of graphene is expected to range from US$100 to US$400 per gram, which is relatively expensive (*Pistilli, 2024*). Thus, the high cost acts as a barrier to widespread adoption of graphene. According to a survey carried out in January 2021, 30% of the surveyed graphene companies and institutions expressed cost as an issue (*Statista, 2023*).

Even so, industries are adopting graphene into their products at alarming rates. Applications for graphene in electronics, including batteries, sensors, and transistors, are growing in popularity. According to a Verified Market Reports analysis, the graphene market's largest and fastest-growing area is electronics, especially due to the relevance of laptops, phones, and other daily electronics today (*Top Trends in Graphene, 2023*). Following suit are other energy based technologies such as batteries, fuel cells, and solar cells, especially because graphene extends their lifespans and durability while also contributing to fewer emissions. While these sectors lead the graphene market, other industries such as composites and automotives are also incorporating the nanomaterial into their products. Fig. 2 below illustrates the distribution of graphene use across various industries (*Industrial Applications of Graphene Based Materials., n.d.*).

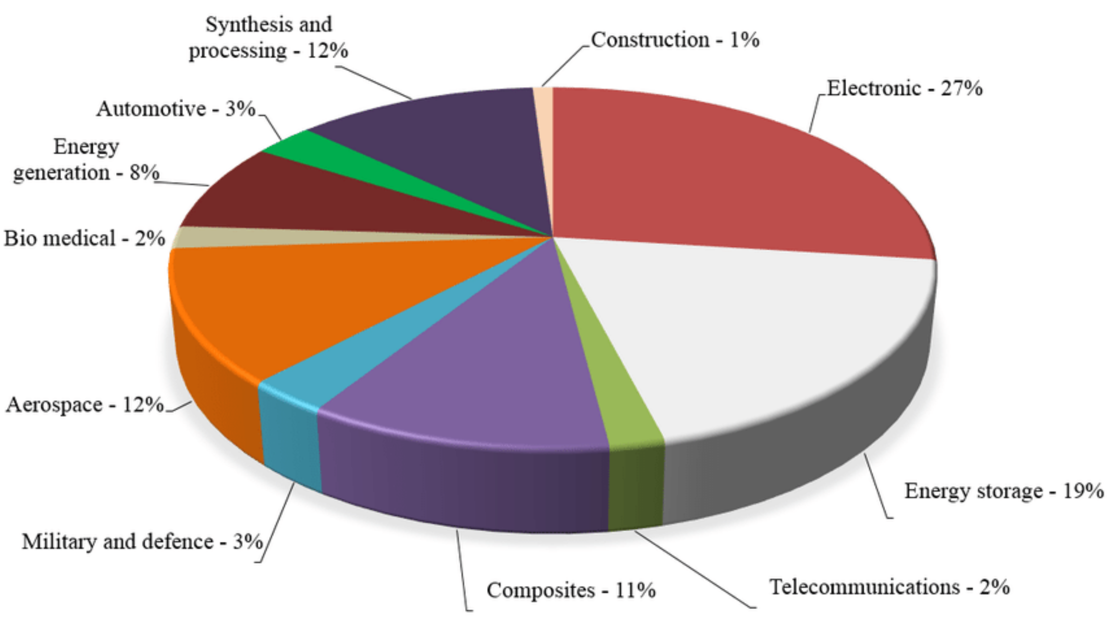

Fig. 2: Distribution of use of Graphene in various sectors

The future of graphene adoption looks promising, with ongoing research and development expected to uncover new applications and drive further integration. As production techniques improve and costs decrease, graphene's disruption across various sectors will likely accelerate, leading to widespread adoption across all industries.

Economic Impact of the Manufacturing of Graphene:

There exist many possible methods to manufacture graphene, and they fall into two categories the 'top down' and bottom up approach.

The top down approach involves synthesizing graphene from its parent allotrope, graphite. The model of graphite and graphene can be better understood using an analogy of a stack of papers. Each singular sheet of paper represents a sheet of graphene. These sheets are packed close together and held as a large stack, which represents graphite. During its manufacture, graphene is synthesized by separating the stack into individual layers, i.e. sheets of graphene. Methods to do this include Mechanical Exfoliation, Pressure Exfoliation, Chemical Exfoliation, and Electrolytic Exfoliation.

Conversely, the bottom up approach involves using chemicals such as methane and hydrogen to produce graphene in its pure form, or as a compound. An example of this is Chemical Vapor Deposition (CVD), which is the most popular method to produce graphene today. This paper will focus on CVD and Electrolytic Exfoliation.

A. *Chemical Vapor Deposition (CVD)*

A.1 Process:

The process of graphene synthesis via CVD involves depositing a solid material from a vapor phase by a chemical reaction on a substrate. The technique relies on the thermal decomposition of a carbon-rich source (usually methane) and the further deposition of carbon atoms in a honeycomb pattern on top of a metallic catalyst film (usually copper) to form graphene sheets (*Hernández et al., 2023*). This process takes place at high temperatures, around 950ºC, with a catalyst (*De La Fuente, n.d.*), and around 2500ºC without one (*CVD Graphene, n.d.*). The thin metal substrate is placed into a heated furnace, where methane and hydrogen gases react with the substrate to prompt graphene growth and production.

A.2 Cost of Production:

The primary raw materials usually involved in this bottom-up process are copper, methane, and hydrogen. These raw materials are readily available, and thus do not impact the cost of production via CVD to a great extent. However, CVD remains an extremely expensive production process. This is because it demands the use of expensive equipment such as a reaction chamber and a quartz tube, which is where the reaction takes place (*Graphene, 2024*). Furthermore, the process is even more financially burdening because it demands high temperatures and a vacuum setting, which categorize it as energy-intensive. According to the General Graphene Corp., the average cost of CVD graphene production ranges from $100 to $400 per square meter (*General Graphene Corp, 2024*).

This poses cost barriers in the production of graphene via this method. It is likely that producers and manufacturing firms choose not to produce graphene as they lack the financial capital to do so. Considering the relevance and widespread application of graphene today, this could hinder the firms' growth and success, while also reducing market supply of graphene from its maximum potential. It also has a spillover effect on fields such as electronics and energy, which are large adopters of graphene. The scarcity of graphene in the market due to this could then slow down crucial innovations in fields such as medicine, where graphene is used for its high sensitivity in biosensors – this would then negatively affect the overall health of the economy, worsening life expectancy. In addition, slowed innovation on electronics and energy would worsen living conditions as consumers suffer from limited choice.

A.3 Lack of Competition:

Due to the high costs, smaller firms would be driven out of the market, likely falling behind their competitors, which could promote the formation of monopolies in the industry. Monopolies are undesirable as they likely abuse their market power by producing low quality products while charging high prices for them, sometimes unaffordable. Furthermore, the lack of competition causes monopolies to become complacent, and reduce their R&D spending, thus reducing international competitiveness and usability of graphene.

Conversely, monopolies could utilize their supernormal profits to invest more in better technology, which would result in a fall in the average cost of production in the long run. This increases efficiency while also making the graphene more affordable, increasing its adoption rate. Currently, the companies Grolltex and General Graphene are leading CVD graphene production, leveraging advanced technologies. An organization called 'The Graphene Flagship' is a large scale research initiative funded by the EU, and has received around €1 billion in funding since its inception (*Graphene Research, Innovation and Collaboration | Graphene Flagship, n.d.).* They will use the funds for R&D, which will drive the economy forward.

A.4 Environmental Impact:

It is also important to note that CVD may release toxic gas byproducts such as carbon monoxide and ammonia, which is considered an environmental pollutant due to its corrosion ability and toxicity (*Saeed et al., 2020*). The toxicity of ammonia could pose numerous health problems such as respiratory issues and eye irritation. The consequences could also become serious; ammonia can cause chronic bronchitis and Reactive Airways Dysfunction Syndrome (RADS) (*Neghab et al., 2018*). For example, in 2017, there were 41 reported workplace deaths from chemical inhalations (*Fatal Chemical Inhalations in the Workplace up in 2017, 2019*); these deaths pose safety concerns and reduce the size of the workforce, thus weakening the economy.

Moreover, due to the complex equipment and high temperatures involved in CVD, it is also an extremely energy-intensive process, which is a burden on the environment. It releases greenhouse gases, contributing to global warming and environmental pollution, which is undesirable and presents the process of CVD as one that causes a Negative Externality of Production for graphene. The Marginal Social Cost (MSC) is greater than the Marginal Private Cost (MPC); thus, graphene is overproduced using the CVD method. The market produces at quantity Q1, however the socially optimal output is at Q. The welfare loss generated is shaded blue in Fig. 3 below.

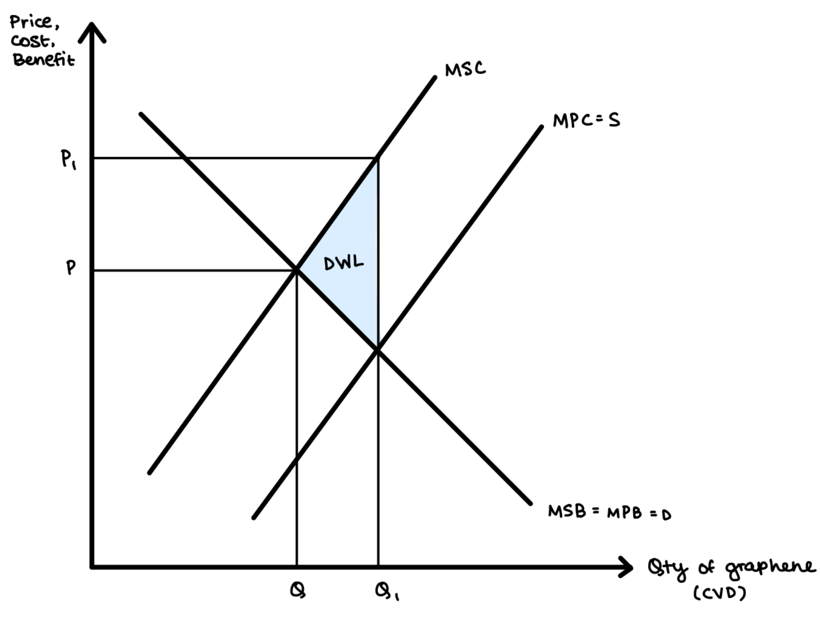

Fig. 3: Negative Externality of Production due to CVD Manufacture

A.5 Overview of Benefits:

Still, CVD remains one of the most popular forms of graphene synthesis. This is because of its high scalability and graphene quality. A CVD process developed by University of Cambridge and Rheinisch-Westfälische Technische Hochschule (RWTH) Aachen University researchers ensures both high yield (>95%), and high quality of the graphene domains (*Burton et al., 2023*). Certain industries require only very high-quality graphene, such as the automobile industry. Other methods of production are lacking in this vein, and thus CVD remains widespread.

Furthermore, given the complexity of the process and the equipment required, firms partaking in graphene production via CVD would require greater amounts of manual labor to power machines involved and monitor the process. Thus, CVD could potentially boost the economy by providing employment opportunities and bringing the economy closer to the Natural Rate of Unemployment (NRU). For example, Lam Research expects its new facility in Oregon, for semiconductor manufacturing with CVD, to create approximately 300 new jobs and career opportunities (*Administrator, 2022*).

B. *Electrolytic Exfoliation (EE)*

B.1 Process:

This top-down process involves the separation of graphite into mono-layer or multi-layer graphene with the help of a simple electrolytic cell, where two oppositely charged, electrodes are connected to a power source and partially immersed in a solution called the electrolyte, containing oppositely charged ions. The technique relies on electrolytic principal, where the positive ions are attracted to the negative electrode (anode) and vice versa. The cathode is made of platinized platinum and is inert, which means it does not partake in the reaction. At the anode, which is made of graphite, ions intercalate (insert themselves between the graphite layers) and force the graphite layers to separate, thus forming graphene. The graphene can then be collected, dried, and used.

B.2 Cost of Production:

The primary raw materials involved in this simple and relatively new method are graphite, platinized platinum, and the electrolyte, which is often an aqueous or acid solution, such as ammonium sulfate or sulfuric acid, respectively. These raw materials are readily available, and therefore do not impact the cost of production to a great extent. Furthermore, the process does not require any specialized equipment, apart from a battery cell. In that vein, electrolytic exfoliation is a low cost method for graphene synthesis (*Qiu et al., 2023*).

Because Electrolytic Exfoliation is still relatively new, it is not yet widespread. However, it has the potential to revolutionize the industry by encouraging the adoption of graphene across a multitude of fields. Firms of all sizes would be willing to incorporate graphene intro their products, as the process is not financially demanding. This results in improved quality of products, resulting in higher living standards. Moreover, the benefit of low resource costs will likely be passed onto consumers in the form of lower prices. A greater number of firms producing graphene increases market supply, thus categorizing graphene as more affordable. According to Graphenea, there has been a rapid rise in the amount of graphene producing companies in recent years (*Spasenović, n.d.).* This is supported by the statistics regarding the growth of the graphene industry, presented in previous parts of the paper.

B.3 Competition:

In addition, this cost-effective method pushes fewer firms out of the market, thus maintaining healthy market competition. This maintains efficiency in the market and incentivizes firms to innovate in order to gain market share and revenue against their competitors, else they would be pushed out of the market due to a high number of substitutes. A high degree of competition also prevents consumer exploitation, and each firm tries to sell their product at the lowest possible price in order to increase their customer base, as firms are profit motivated.

B.4 Environmental Impact and Duration:

Furthermore, the process has a short synthesis duration, which make it easier for firms to alter production as an when necessary, increasing elasticity of supply. The market becomes more responsive, and thus further efficient. Another advantage of this process is that it is highly scalable, green and environmentally friendly (*Abbas et al., 2022*). It releases no harmful gases or chemicals, thus having no negative effect on the environment. The non-toxic nature of the chemicals used in the process also prevents it from having any effect on the health of citizens. This prevents the worsening of living standards while maintaining social and economic welfare. Although it requires a power source, the process is not energy-demanding, making it a good option for graphene production.

B.5 Quality of Graphene:

Conversely, there do exist reasons why electrolytic exfoliation of graphene is not the most widespread method. These problems lie in the yield and quality of graphene produced due to the disconnection of large graphite chunks falling in the electrolyte through the process. Researchers at the University of Sydney in 2019 tried to tackle this issue by raising the voltage, but found that it resulted in lower quality graphene with higher defect density, though yield rose (*Liu et al., 2019*).

Low yield and low quality graphene are economically unfeasible, as they would require the process to be repeated multiple times in order to produce a sufficient amount of graphene, which introduces cost concerns once again. Furthermore, firms may be less willing to indulge in research and development in graphene technologies given uncertain economic returns. Widespread adoption of this method would lead to supply chain inconsistencies which would often disrupt not only the graphene market, but also have a spillover effect on the industries that are large consumers of graphene, such as electronics.

B.6 Overview of Benefits:

However, researchers at the Guangxi Normal University in China have now developed modifications to the process that attempt to remedy these problems. With their modifications of 'flexible encapsulated graphite with filter cloth as both anode and cathode', graphene yield increased by more than 25% (*Qiu et al., 2023c*). It was also found that electrolytic exfoliation can produce few-layer, low-defect graphene, with an 80% conversion efficiency (*Huang et al., 2012*). Furthermore, because electrolytic exfoliation is a continuous process, it was found to produce large quantities in short periods of time, making it suitable for industrial use.

C. *Numerical Cost Models – CVD vs EE*

The differences between CVD and electrolytic exfoliation can be further examined by building a manufacturing cost model for each. The models below are theoretical models based on a multitude of assumptions.

(PTO to proceed)

C.1 Cost Model for CVD

This model has been developed in order to predict the cost of manufacturing graphene at an industrial scale facility. The assumptions made are outlined in Table C.1.1 below.

No.	Key Assumption
1	The industrial scale facility has 10 CVD furnaces
2	# of years of amortization is taken as 5
3	20 workers are required for each industrial scale facility
4	The efficiency of output of graphene will improve by 100x in industrial vs lab furnace given that each lab scale CVD furnace produces
5	The usage efficiency of variable inputs will improve by 100x in industrial vs lab furnace
6	Copper recycling and wastage rate are negligible
7	Rent for industrial scale facility is 2x of lab facility

Table C.1.1: Key Assumptions (CVD)

The input metrics in Table C.1.2 below were used, along with numerical assumptions stated in Table C.1.1, to compute the output metrics in Table C.1.3. Certain assumptions have been reinstated in Table C.1.2 for ease of calculation. Other factual data (cost of industrial scale furnace, production capability of lab scale furnace, etc.) used in calculations is also stated and cited in Table C.1.2.

Input Metric	Variable/Cost
# of CVD furnaces	10
Production Capability of graphene per year (lab scale furnace)	4500 m^2
Cost of each industrial scale furnace	$250,000
Mass of graphene	0.00077 g/m^2
Years of amortization	5
Copper/waste recycling rate	0%
Total # of workers	20

Table C.1.2: Input Metrics

Output Metric	Variable/Cost
Total graphene output (industrial scale, 10 furnaces/year)	4500000 m^2
Total graphene mass (industrial scale, 10 furnaces/year)	3465g

# of sq mtr required per gram of graphene	1299

Table C.1.3: Output Metrics

In order to calculate the fixed and variable costs of an industrial facility, data for lab scale CVD production was adjusted using key assumptions already stated. This base data was sourced from research by Henry M. Hanlon at the Massachusetts Institute of Technology (*Hanlon, 2020*), who investigated CVD costs at a lab-scale. The calculations are expressed in Tables C.1.4 and C.1.5.

Factor	Cost
Rent	$120,000
Facilities	$50,000
Equipment	$500,000
Labor	$300,000
Total Fixed Cost	$970,000
Avg Fixed Cost (per gram)	$280

C.1.4: Annual Fixed Costs

Factor	Cost
Key Gases	$0.01
Energy	$0.02
Copper	$0.04
Total Variable Cost	$0.06
Avg Variable Cost (per gram)	$82

C.1.5: Variable Costs (per sq mtr)

Thus, the average cost of manufacturing is calculated by adding average variable cost and average fixed cost, giving $362 per gram. This establishes CVD graphene as very expensive, confirming anecdotal and qualitative data expressed in previous sections of the paper.

<u>C.2 Cost Model for EE</u>

Since there is no existing data for Electrolytic Exfoliation, key assumptions have been made based on previous knowledge and cost data that is readily available. Cost for raw materials, supplies and conversion ratios have been obtained based on discussions with Prof A. S. Khanna (Retd. IIT Bombay & Graphene Expert in Electrolytic Exfoliation in India). These have all been outlined in Table C.2.1 below.

No.	Key Assumption
1	The industrial scale facility has 10 EE bays
2	# of years of amortization is taken as 5
3	20 workers are required for each industrial scale facility
4	Each EE bay is capable of converting 1000kg of graphite into graphene per year
5	Each bay can handle 4kg of graphite conversion per day
6	Conversion efficiency of graphite to graphene is 50%
7	30% of graphene flakes from EE will be usable
8	Energy consumption is 10KwH per gram of graphene
9	Graphite (main raw material) costs $20/Kg
10	Cost of equipment for each bay is $25,000
11	Cost of electrochemical supplies (cathode, electrolyte, etc.) is $120/kg
12	500g of other supplies are required per 100g of graphene produced

C.2.1: Key Assumptions and Costs (EE)

This information was then used to identify key input metrics in Table C.2.2, which were used to compute the output metrics in Table C.1.3. Certain assumptions have been reinstated in Table C.1.2 for ease of calculation.

Input Metric	Variable/Cost
# of EE bays	10
Total Cost of Setup, Base Equipment per bay	$25,000
Years of amortization	5
Total # of workers	20

Table C.2.2: Input Metrics

Output Metric	Variable/Cost
Total graphene output (industrial scale, 10 bays/year)	5,000,000g

Table C.2.3: Output Metrics

In order to calculate the fixed and variable costs of an industrial facility, cost data from discussions with Prof. A.S. Khanna was used. The calculations are expressed in Tables C.1.4 and C.1.5. Rent, labor and facility costs were kept constant to ensure a fair comparison.

Factor	Cost
Rent	$120,000
Facilities	$50,000
Equipment	$50,000
Labor	$300,000
Total Fixed Cost	$520,000
Avg Fixed Cost (per gram)	$0.10

C.1.4: Annual Fixed Costs

Factor per gram	Cost
Graphite	$0.04
Energy	$1.16
Supplies	$0.60
Avg Variable Cost (per gram)	$1.80

C.2.5: Variable Costs (per gram)

Thus, the average cost of manufacturing is calculated by adding average variable cost and average fixed cost, giving $1.90 per gram. However, considering efficiency limitations of EE outlined in the assumptions, it is necessary to adjust the cost to consider only useable quantities by 30%, giving $6.33 /g.

Building a similar model for electrolytic exfoliation shows that the cost of graphene manufacturing falls dramatically to $6.33 /g even after adjusting for graphene quality. This is primarily because there are no significant costs of equipment and raw materials vs CVD. However, it is important to remember the various other limitations EE has, outlined in previous parts of the report.

D. *Comparative Analysis / Summary*

Both CVD and electrolytic exfoliation are stellar methods for the production of graphene. CVD is the most popular and widespread, while EE is a new method with huge potential for the future. Below is a summary of the findings, comparing the two graphene synthesis methods.

CVD	**EE**
Expensive due to complex machinery and equipment required ($362/g)	Cost effective due to a simple setup ($6.33/g), encouraging more firms to use graphene
Environmentally unfriendly	Sustainable and no environmental impact

Scalable	Scalable
Very high yield	High yield
Higher quality graphene	Lower quality graphene

Given the importance of the environment and sustainability today, it is also important that certain policies are undertaken to reduce the harsh environmental impact due to the widespread use of CVD. For example, CVD producing firms who do not require high quality graphene could be taxed higher to push them to switch to other options such as EE. This should be done at least until significant improvements are made in the field of EE.

Overall, CVD-produced graphene to be suitable for all its applications. However, ongoing research in EE is slowly resulting in minor alterations to the process that improve the process on three fronts: yield, quality, and scalability. Due to this successful ongoing research centered around electrolytic exfoliation, it has huge potential for the future. It already possesses a vast number of advantages, and the research has the ability to push it to being the economically optimal method for graphene synthesis in the future.

Economic Impact of the Use of Graphene:

Graphene has a multitude of applications in a variety of fields, including biotechnology, electronics, energy storage, coatings (composites), automotives, and water filtration, among others, as seen in Fig. 2 in previous parts of the paper. The high versatility of the material allows it to be used in different forms in all its applications. For example, the adoption of graphene in biotechnology is very new, but the nanomaterial's high sensitivity has proven to improve biosensors, thus detecting diseases much faster, and saving lives (*Ping et al., 2016*). Further, its oxidized form, graphene oxide (GO), provides a large surface area and low cytotoxicity, making it suitable for medical applications (*MRYuvatha, n.d.*). This paper will focus on the application of graphene in water filtration and Li-ion batteries.

A. *Water Filtration*

The most common way to incorporate graphene into water filtration and desalination systems is through graphene oxide (GO) membranes. These are made by suspending GO in water, which is then cast on to a support membrane, helping form its own membrane (*Woldu, 2023*). These membranes are then incorporate as layers of filtration devices.

This improves the product because GO membranes have high permeability due to their porous structure (*Aghigh et al., 2015*), which enables fast water flow, and majority of the water to pass through, preventing wastage of a scarce resource. The membranes, as all graphene-based materials do, have antibacterial properties. These filters thus prevent consumers from obtaining water-borne bacterial infections or diseases. Lastly, they act as selective filters, with desalination properties that can remove even the smallest ions, and adsorption abilities that remove dangerous heavy metals such as lead, arsenic, and heavy mercury (*Schmidt et al., 2023).*

Research by Nanografi showed that in comparison to regular water filters, graphene water filters are considerably more efficient since the quantity of pure water that this these filter produce is 8-9 times greater than that of commercial water filters (*Graphene Water Filtration, n.d.*). With widespread integration of these water filters, the economy would become healthier. Not only do living standards increase, but so does productivity. With fewer people falling ill, workers take fewer sick days; this has a positive effect on overall output of the economy, boosting GDP and thus international position.

Moreover, research by Jeffrey Grossman, a professor at MIT, shows that the process of pumping seawater through filters represents about half the operating costs of a desalination plant (*MIT Energy Initiative, 2016*). He says that by using graphene filters, plants would use 50% less energy. This is an impressive reduction on the amount of energy used, and again has widespread effects. It cuts down on the firms energy costs, reducing their overall cost of production. This gives them more money to invest in R&D, which results better quality products in the long run. It also reduces environmental harm by 50%, due to 50% fewer energy emissions.

In addition, clean water is one of the goals of sustainable development set by the United Nations (*Use of Graphene in Water Filtration, n.d.).* Using graphene based filters would result in a larger volume of cleaner water that is readily available. This helps push economies to being more sustainable by conserving resources, while maintaining, or even improving the economy's performance. In addition, resource conservation promotes a stable economy by ensuring the availability of scarce resources in the long run, thus promoting certainty, which allows consumers to buy products and businesses to invest with confidence.

Furthermore, the emergence of new and sustainable innovations, such as the graphene filter, will likely drive innovation, leading to new products, services, and markets. This enhances the competitiveness of businesses and ensure firms do not exploit customers by charging high prices, while also being responsive and efficient in order to stay in the market.

Firms and researchers will become more aware of graphene and experiment with its other uses and application in sustainability. For example, an article published recently in 2024 by Dr. Subrahmanya Rao presents graphene as "The Game-Changer" in sustainable waste management and recycling (*Future, 2024).* This is something that has never been explored in depth in the past. However, if research continues and proves to be successful, this is a new concept that has the potential to revolutionize sustainability in the way water filters have, and promote a green economy. According to the International Labor Organization (ILO), the green economy could create 24 million new jobs globally by 2030 (*24 Million Jobs to Open up in the Green Economy, 2024*).

Furthermore, the potential environmental benefits that stem from switching to graphene-based water filters is commendable. Not only do current water filters rely on activated charcoal (an unsustainable resource), but are also not as effective as graphene. In fact, using sustainable graphene-based water filters can removes 3 to 65-fold more heavy metals (lead, cadmium, and mercury) from tap water. Given the reusability and higher efficiency of graphene, this would ultimately lead to lower production of coal-based water filters, corresponding to a reduction in energy consumption and carbon footprint.

The ripple effect that graphene water filters can have on public health, resource conservation, and the economy prove that it has a vast array of external benefits. This classifies the graphene water filters to have a Positive Externality of Consumption, where the Marginal Social Benefit (MSB) is greater than the Marginal Private Benefit (MPB), generating an external benefit which is represented by the gap between the MSB and MPB curves. The market produces at quantity Q1, however the socially optimal output is at Q. The welfare loss created is represented by the shaded area in Fig. 4 below.

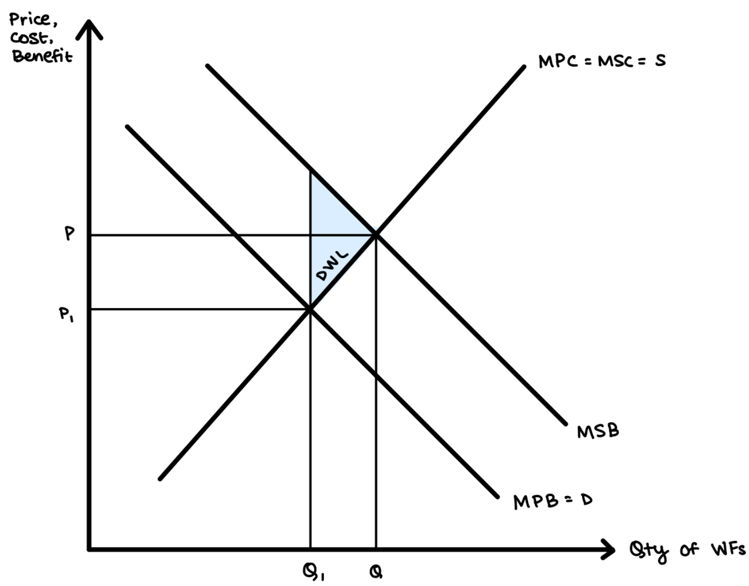

Fig. 4: Positive Externality of Consumption due to Graphene WFs (Water Filters)

Clean water is a vital resource in every household, whether to cook, clean, or drink, and is also essential in many manufacturing processes. These graphene filters could thus be integrated seamlessly.

B. *Li-ion Batteries (LIBs)*

Graphene can be incorporated into lithium ion batteries in two main ways. The first is by replacing the typical graphite anodes in batteries with graphene anodes (*Qi et al., 2024*). To reiterate, graphene has the same properties and graphite, however each quality is far stronger. This results in the batteries having higher capacities (thus being longer lasting) as well as faster performance, due to graphene having high electrical conductivity. The second method is by coating the cathode of the battery with graphene (*Kaur & Gates, 2022*). The graphene layer acts as a protective barrier that prevents the dissolution of the cathode material into the electrolyte. This also helps prevent the growth of lithium dendrites, which can cause short circuits and potentially lead to the battery catching fire or exploding, according to research conducted in 2023 (*Qi et al., 2024b*).

Regardless of the method, the integration of graphene in LIBs can be extremely beneficial. Graphene's high thermal conductivity helps dissipate heat more effectively, preventing overheating and enhancing the safety and longevity of Li-ion batteries (*The Graphene Council, n.d.*). As per a report published by Newark Electronics, the battery life of a typical LIB is about 300 to 500 charge cycles (two to three years) (*Tektronix, n.d.).* Conversely, according to research in 2020, the lifespan of a graphene enhanced LIB is often far longer, around 1,000 to 2,000 charge cycles (five to seven years), depending on specific conditions (*Ali et al., 2022; Lavagna et al., 2020*). Further studies have shown graphene-enhanced batteries retaining up to 88% of their initial capacity even after 1,000 cycles, compared to about 60-70% for conventional LIBs after 500 cycles (*Bellini, 2021*).

This has vast economic benefits. To begin with, consumers are positively impacted, due to their immense cost savings. While they would normally have to replace their LIBs every two to three years, they would now have to replace them every five to seven years, considering the graphene-enhanced LIBs have much higher longevity. This would not only affect the consumers who are directly buying LIBs, but also spillover to goods in which LIBs are used, such as smartphones, electric cars and other electronic devices. This vastly cuts back consumers' annual expenses, resulting in higher disposable incomes, and the ability to purchase a more goods and services.

Graphene-enhanced LIBs also have an effect on consumer convenience. According to an article by Automation Switch, if a lithium-ion battery achieves a full charge in one hour, a graphene enhanced LIB would achieve the same charge in just 12 minutes. This makes products with graphene LIBs lucrative to consumers, increasing their demand. Likely, this will result in more firms adopting the graphene-enhanced LIBs into their products, increasing competition, resulting in a more efficient market.

The competition also promotes R&D, which sparks innovation and boosts product quality. For example, Samsung SDI, the battery manufacturing arm of the firm, has developed 'graphene balls' that could make lithium-ion batteries in their phones last longer (while offering 45% increased capacity) and charge 5 times faster (*Anmol, 2019; Samsung Develops Battery Material With 5x Faster Charging Speed, n.d.*). The phones are said to fully charge in half an hour. Tesla is another company that seems to have taken interest in enhanced batteries for their EVs (*Lambert, 2022*).

In addition, longer-lasting batteries reduce the frequency of disposal and demand for raw materials, leading to decreased environmental pollution and resource depletion. This is especially important for metals like lithium, cobalt, and nickel. With graphene LIBs that last 2-3 times longer than regular LIBs, the amount of waste generated by batteries and battery manufacturing would reduce by half or even more. Another notable benefit is that graphene LIBs will reduce dependency on batteries with heavy metal components which pollute our planet's resources. This is specifically beneficial for aquatic life, usually affected by battery waste, such as fish and marine mammals (*Times of India, 2024*). The ingestion of battery fragments or toxic chemicals can cause internal injuries, organ damage, and even death. Moreover, the extended lifespan of graphene-enhanced LIBs supports the principles of a circular economy, where products are designed for longevity, reuse, and recycling, leading to sustainable economic growth.

However, graphene LIBs are yet not at the widespread level they are expected to be. This is because they require high-quality graphene, best manufactured by CVD. This is an expensive process, as described in the earlier sections of the paper. Thus, the graphene-enhanced LIBs suffer from higher production costs, especially considering the battery manufacturing process is already complex, requiring expertise. These costs are conveyed to consumers in the form of higher prices. For their longevity, the return is high. However, many consumers and firms view their purchases only in the short run, and thus may refrain from purchasing these LIBs, thus restricted their widespread adoption. They may also refrain from purchasing graphene-enhanced LIBs due to it being a newer technology, or due to brand loyalty; the higher costs of graphene-enhanced LIBs can make further challenging for them to compete with well-established conventional LIBs in the market. One way to remedy the issue is to educate consumers and firms, and highlight the importance of a long-run perspective. The other, which is currently being researched, is methods to bring down the cost of producing high quality graphene, either via a different method, or by modifying CVD.

Conclusion:

Graphene, one of the most important nanomaterial discoveries of the 21st century, has shown promise to revolutionize various sectors of the global economy. This report examines the economics surrounding Graphene, market dynamics, manufacturing options and practical applications (through water filtration and lithium-ion batteries).

At an overall level, the Graphene market is one of the most exciting and fastest growing segments in the nano materials sector, as supported by current projections, which indicate a CAGR of 31.8% from 2024 to 2032. This growth is expected to be driven by continued research and development, improving production techniques, and expanding applications across various industries.

Further, while CVD is the more dominant form, it is costly, consumes more energy and also has climate and environmental concerns. However, it produces higher quality Graphene. Electrolytic Exfoliation, on the other hand, is a newer technology. While it produces lower quality Graphene, it is more environmentally friendly and affordable. R&D is ongoing, and it is very likely that we will see new developments in the coming years regarding the manufacture of graphene.

Moreover, 2 promising areas of graphene application are its use in water filtration and Li-ion batteries. Graphene-based water filters are significantly better than traditional water filters specially in efficiency, energy consumption, and water quality, contributing to public health, resource conservation, and sustainable development. With the widespread use of lithium ion batteries, the use of Graphene promises longer lifespans, faster charging times, and improved safety, which could drive innovation in electronics and electric vehicles while supporting a more circular economy.

To sum up, within the current context of our planet and the significant issues being faced by the human race, especially in global warming and sustainability, Graphene can play a very important role in the future. It can promote energy conservation and lead to the development of more sustainable products, driving innovation. The future of graphene looks very promising.

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