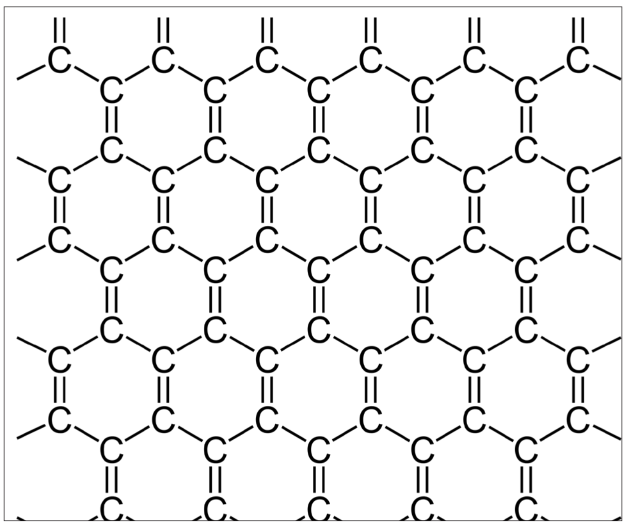
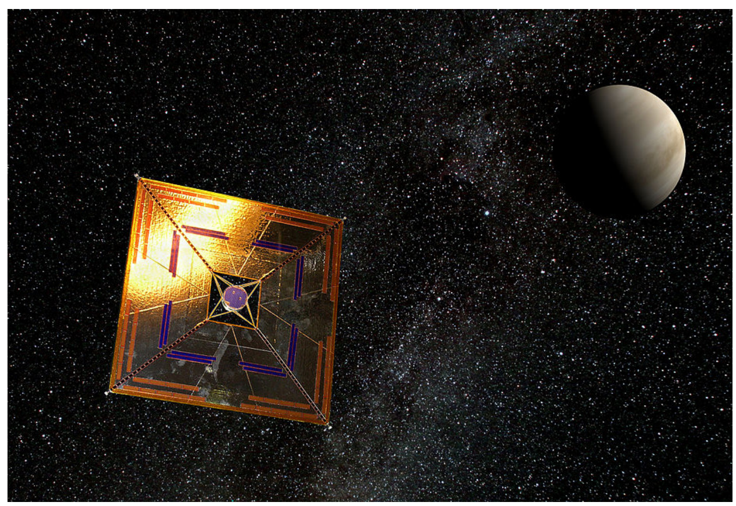
Cornering the Graphene Market

Countering Beijing's Strategy for Industry Domination

Lindsey | Washington





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Countering Beijing's Strategy for Industry Domination

Graphene is a one-atom thick, semimetal superconductor that promises to revolutionize several industries key to national security. The Chinese government has invested heavily in research and development for the cost-efficient production of graphene, allowing China to undercut global competitors and limit market entry in the long run. Control over the graphene market will strengthen China's presence in the energy and space industries, improve its armored vehicles and body armor, and bolster its influence in regions crucial to U.S. national security. Because the United States has not prioritized graphene production research, it will be unable to strategically or commercially compete as China dominates the graphene market. To combat Chinse industry domination, the United States can use existing research and manufacturing infrastructure within the Department of Defense to develop cost-effective graphene mass production processes.

Introduction

Graphene is characterized by energy storage, electric and thermal conductivity, particle filtering, elasticity, and mechanical strength. Because of these properties, graphene has applications in the renewable energy, aerospace technology, armor production, and water desalination industries. Despite its potential, the difficulty of mass-producing high-quality graphene prevented its widespread use in the years following its discovery in 2004.[1] However, market analysts examining recent advancements toward scalable production, largely by Chinese-funded labs, predict that the graphene market will reach $311.2 million by 2022, a 760 percent increase from 2015.[2]

With a hold on the graphene market, China will have an advantage in the production of better alternatives to current lithium-ion and supercapacitor technology, will develop superior satellites and more efficient lasers, will build less costly water desalination plants, and can produce lighter-weight, stronger armor. Because of current production capacity deficits, the United States will not be able to recoup the advantage Beijing will hold in global markets.

While Beijing's subsidies and funding allow Chinese graphene firms to innovate mass production processes, the U.S. research and development apparatus lacks similar incentives. Silicon Valley operates primarily through the interaction of innovative startup firms and venture capitalists driven by profit incentives.[3] Because research and development into graphene mass production is not currently profitable, Silicon Valley has little motivation to innovate. To bridge this gap, the United States should take advantage of existing infrastructure within the Department of Defense to fund research into graphene mass production.

Graphene: A New Material for National Security

> *Experts say the 20th century was a century of silicon, and that this century will be one of carbon materials like graphene.*
>
> -Ma Qing, President of Baotailong New Materials, 2018[4]

Graphene is strong, extremely lightweight, and flexible. It conducts heat and electricity nearly as well as superconductors but does not need to be cooled to low temperatures. Because of these characteristics, graphene has the potential to transform a wide range of industries and products. Despite its promise, however, the global graphene market remains stagnant because high-quality graphene is prohibitively costly to mass produce. A variety of research labs around the world, the majority of which are Chinese or Chinese-funded, have taken steps forward toward solving these mass production challenges.

The Properties of Graphene

Graphene derives from carbon and is approximately 200 times stronger than steel, making it the strongest material yet discovered. Graphene is also remarkably lightweight.[5] Unlike steel, graphene is not stiff, but rather both firm and elastic—a material akin to rubber. Because of this flexibility, graphene can be stretched to approximately 20 to 25 percent of its original length.[6] As a conductor, graphene surpasses both silver and copper and performs nearly as well as a superconductor. However, unlike superconductors, which need to be cooled to low temperatures, graphene retains its conductivity at room temperature, decreasing the energy requirements that traditionally constrain superconductors.[7]

Because of its mechanical, elastic, and conductive characteristics, graphene has a wide range of applications salient to U.S. national security. Its strength and weight relative to today's leading materials will make graphene an effective substitute for steel. In 2017, for example, an MIT research team successfully created a sponge-like configuration with a density of just five percent and a strength ten times that of steel by compressing and fusing flakes of graphene.

The Production of Graphene

There are two basic methods of producing graphene: cleaving multi-layer graphite into a single layer or growing graphene epitaxially by depositing a layer of carbon onto another material. Although these processes are effective at producing small, high-quality batches of graphene, they are energy wasteful and prohibitively costly.[8] For example, yielding one kilogram of graphene currently requires one ton of organic solvent.[9] These environmental and cost challenges have depressed the nascent graphene industry.

In recent years, research teams in China, Singapore, and the United States have made progress in solving production challenges that impede the mass production of graphene. For example, Shenzhen Danbond Technology, a company based in China, announced in July 2018 that it had begun mass production trials of a self-developed graphene product.[10] Engineers at MIT, meanwhile, have successfully developed a manufacturing process for long strips of high-quality graphene suitable for microporous water desalination filters. Finally, a Singaporean research team has developed a method that requires 50 times less solvent to produce graphene.[11] As a result of these, and other teams', advancements in graphene production, market analysts predict that the graphene industry will mature over the next few years.[12] However, China is far outperforming U.S. research and development into graphene, leaving Beijing poised to corner the emerging market.[13]

The Geopolitics of Graphene Applications

> *We are approaching a tipping point. In 12 to 18 months, you will start to see graphene products hit the marketplace at an ever-increasing pace.*
>
> - James Baker, chief executive of Graphene@Manchester, 2018[14]

Graphene promises to revolutionize several industries key to U.S. national security, including the energy and space industries, armor production, and water desalination. In the global energy industry, Chinese domination of the graphene market will allow Beijing to undercut battery competitors. In the space industry, graphene will afford Beijing the capacity to put a greater number of technologically superior satellites in the air, as well as weaponize these satellites quickly. For armor production, graphene will allow China to produce light-weight, flexible armor, which it can use to increase the efficacy of its troops, as well as it geopolitical influence. Finally, in water desalination, graphene will allow Beijing to offer cheap, vital technology to Middle Eastern states, increasing its regional influence, while distancing U.S. partners from Washington.

Batteries

As the global energy paradigm continues shifting from fossil fuels toward renewable resources, energy storage for power sources, such as solar and wind, remains elusive. As a result, researchers increasingly look toward large-scale energy storage systems like lithium-ion batteries and supercapacitors.[15] While lithium-ion batteries that rely on chemical reactions are the most common form of energy storage, they are also liable to quick degradation or permanent capacity loss. Supercapacitors, on the other hand, store energy in an electrical field, lengthening their lifespans.[16] Despite this advantage, current supercapacitor technology has yet to overtake lithium-ion batteries in consumer products because current capacitors hold less energy per unit than lithium batteries and therefore must be charged more often.

Graphene offers a solution to the challenges posed by both lithium-ion batteries and supercapacitors. For example, when applied to the cathode, or the positive side of the battery, graphene increases the durability of lithium-ion batteries, thereby slowing their degradation.[17] Moreover, the relatively large surface area of graphene, which determines supercapacitor performance, gives it the potential to radically decrease the charging time and increase the battery life of supercapacitors.[18] As a result, graphene promises to improve both lithium-ion and supercapacitor technologies, allowing them to become practical for use in consumer devices and broadening the possibilities for energy storage.[19]

Research teams have taken strides toward translating graphene's theoretical potential to real products. For example, in 2017 Samsung released a prototype "graphene ball" that, when applied to the cathode of existing lithium-ion batteries, decreased charging times and improved battery durability.[20] Also, last year Dongxu Optoelectronics, a Chinese-based battery company, announced the successful production of a graphene supercapacitor prototype "with the capacity of a typical laptop battery that could charge up in 15 minutes, instead of a few hours".[21]

Demand for higher-quality batteries exists in both the public and private spheres. In the public sphere, the U.S. military requires longer-lasting batteries in both soldier packs and vehicles in order to improve mobility.[22] Changing global dynamics necessitate greater military mobility and smaller tactical teams. By improving existing lithium-ion batteries and supercapacitors, graphene will allow the military to integrate more unmanned and battery-powered vehicles into its fleet, increasing mobility. Moreover, graphene may be a substitute for costly refueling depots.[23] In the private sector, consumer markets are also eager for a cost-effective substitute for lithium-ion batteries.[24] For example, the introduction of graphene technologies could solve issues of insufficient battery life for the electric car and mobile phone industries.

Japan and South Korea currently lead the global battery market; however, China is making inroads into lithium, an important component of batteries.[25] For example, China's Lischen Battery Co., Tianqi Lithium, and Bak Battery are investing in battery innovation and increasing control over the supply of battery inputs. For example, in 2017 China's lithium firm Tianqi Lithium acquired a quarter of the Sociedad Química y Minera de Chile, the largest lithium producer in the Lithium Triangle region of South America.[26] As a result, China has secured access to over 54 percent of the global lithium supply.[27]

Should China corner the market on both graphene and lithium, it will be able to innovate lithium-ion and supercapacitor technologies, undercut Japanese and Korean competitors, and dominate the global battery market. As demand for better batteries increases, China's chokehold could generate significant domestic economic growth. China's dominance in the battery market will also allow it to leverage technological superiority to move closer to both U.S. allies and adversaries, weakening the U.S. geopolitical position. However, by investing in graphene research and development for mass production, the United States has a chance to undermine Chinese maneuvering in the battery market and encourage U.S. economic growth.

Satellites and Lasers

Solar sails are the most energy efficient method of satellite propulsion.[28] These sails harness the energy of the sun, allowing satellites to abandon costly fuels and travel longer distances.[29] Recent studies indicate that graphene promises to further improve satellite propulsion. Evidence from the Graphene Flagship demonstrates that laser radiation directed at graphene sails creates stronger propulsion with less energy than traditional solar sails. This method produces a new, lower-cost generation of satellites with longer life spans.[30] Furthermore, graphene stands to increase the efficiency of satellite thermal management. Researchers have shown that using graphene-water nanofluids within the heat-loop pipes required for satellite thermal management increases efficiency.[31]

Graphene thermal management may also improve current laser technology. Ultrafast lasers, which use rapid pulses of energy to increase power, make up the vast majority of today's lasers. Currently, researchers use mode-locked lasers with semiconductor saturable absorber mirrors (SESAM) to generate ultrafast pulses; however, SESAM production is complex, and its saturable band absorbers, which collect and diffuse energy and heat, are limited.[32] Multiple research teams have determined, however, that graphene is a promising new saturable absorber.[33] For example, researchers at the National University of Singapore successfully used a layer of graphene as a saturable absorber in a mode-locked fiber laser, enabling a new generation of low-noise and inexpensive lasers.[34] With better functioning saturable absorbers, therefore, weaponized lasers may become efficient enough to be introduced to a wider range of defense applications, including those in space.[35]

Maintaining a strong satellite presence in space has become indispensable for the United States. Satellites allow the United States to maintain GPS, intelligence surveillance, and communications, all of which are necessary for the function of both domestic institutions and national security.[36] At the same time, space exploration offers opportunities for scientific discovery and national prestige on the global stage. The number of states with space capabilities has increased significantly. As a result, the United States finds itself vulnerable in a key national security arena.

Despite government motivation to maintain U.S. leadership and freedom of movement in space, innovation within the U.S. space apparatus has stalled, while that of other states continues to progress.[37] Of the states with emerging space capabilities, China is the most formidable competitor. For example, in January 2019 China successfully landed the Chang'e 4 lander-rover on the far side of the moon—the first successful attempt in history.[38] Moreover, while the United States and Russia have reached stable levels of information sharing and mission cooperation, China remains secretive about its technology and motives.[39] Should Beijing use graphene to develop better satellites, the proliferation of satellites within the Chinese space program would threaten U.S. leadership and freedom of movement in space.

While current international space treaties ban the weaponization of space, they remain unenforceable and China is openly developing weaponized space technology.[40] If Beijing successfully integrates its graphene research into the space industry, it has the opportunity to develop cost-efficient satellites and energy-efficient lasers. With better lasers, China will possess better satellites and space weaponry than the United States. Should the current international space framework crumble, the United States would be left with little time to react.

Water Desalination

Water scarcity, in part driven by rapid urbanization, population growth, and climate change, will leave two billion people, particularly in the Middle East, Sub-Saharan Africa, and the Pacific Island, without access to potable water in the next ten years. As a result, many states in these regions are turning to water desalination plants to meet rising water demand; however, the current generation of water desalination plants are costly and energy inefficient.[41]

Current water desalination facilities use reverse osmosis, "in which water is pumped at high pressure through semipermeable membranes that remove salt and other minerals."[42] Despite advances in technology, however, water desalination remains both costly and inefficient. For example, a thousand gallons of freshwater from a desalination plant costs the average U.S. consumer $2.50 to $5, compared to $2 for conventional freshwater.[43] Recently, however, researchers have taken steps toward developing better technology. For example, a research team funded by the National Natural Science Foundation of China produced a graphene microfilter, allowing for faster and higher rates of water permeation and a higher rejection of salt.[44] This research demonstrates that because of its close-knit atomic makeup, microporous sheets of graphene are an effective substitute for current filters used in reverse osmosis processes, increasing the energy efficiency and decreasing the cost of current desalination technology.[45]

Of the regions impacted by water scarcity, the Middle East is most significant to U.S. foreign policy. Because of its prominence in the global energy market, stability in the Middle East often determines the stability of oil prices on the global market. The United States meets 60 percent of its oil needs through imports, 40 percent of which come from OPEC.[46] Despite its newfound role as oil exporter, the United States has a vested interested in maintaining Middle Eastern security.

To balance regional politics with U.S. national security, the United States relies on cooperation with partners such as Jordan, Egypt, Kuwait, Bahrain, Morocco, and Israel. Israel also works closely with the United States on counter terrorism operations, cyber defense, and balancing against Iran.[47] Moreover, the United States relies on military bases in Qatar to maintain its position in the region. Each of these allies will increasingly rely on water desalination technology in the coming years.[48] If China can offer these countries affordable substitutes for current water desalination technology, it can effectively assert its influence into the region.

Armor

Graphene's light weight and thin nature allows researchers to layer it several times without adding excessive weight.[49] This characteristic of graphene, in addition to its relative flexibility and strength, suggests that layered graphene may act as a substitute to current armor technology. Recently, researchers with the City University of New York determined that two layers of stacked graphene hardens to a diamond-like consistency upon impact.[50] As a result, graphene may enable a new generation of extremely lightweight armor, with applications in both body armor and armored vehicles.[51]

Since the end of World War II, the United States has assumed the role of global leader, requiring significant engagement in international affairs. A key element of that role is to defend and promote the U.S.-led liberal international order with the support of its allies.[52] Other key elements are defending and promoting democracy and human rights, while resisting illiberal forms of government where possible, as well as opposing the emergence of regional hegemons in Eurasia. Because of these responsibilities, the United States must continue to respond to global crises and will become involved in global conflicts through limited peacekeeping, disaster relief, and counter-terrorism missions.

While the U.S. military is unmatched on the conventional battlefield, it is ill-prepared to fulfil its global role in today's changing conflict dynamic.[53] Global conflict is shifting away from set battlefields towards increased mobility and organizational flexibility. For example, rapid urbanization will push U.S. forces to engage adversaries in urban settings, increasing the need for close-quarters combat. At the same time, the rising prevalence of powerful non-state actors necessitate new U.S. military strategy, as will rising numbers of ungoverned regions within failing and failed states.[54] As a result, the U.S. armed forces need equipment that allows for increased mobility and protection when engaging in close combat settings.

Graphene-based armor is lightweight, strong, and flexible. It can be applied to both U.S. soldiers and armed vehicles, allowing U.S. armed forces to become more mobile and better address the proliferation of non-state actors and no-go zones.[55] In addition, by decreasing the weight of body armor, the military can increase the coverage of body armor without sacrificing utility, thereby better protecting U.S. forces in urban settings.

Driven by Profit: The Weakness of U.S. Research and Development

> *Its government-led pursuit of dominance in crucial industries presents a direct challenge to countries where leaders generally leave business decisions to the businesses themselves.*
>
> -Kieth Bradsher, The Ney York Times, 2017[56]

Despite considerable scientific and market interest in developing graphene-related products globally, U.S. graphene research is relegated to small research labs. Profit drives the U.S. research and development apparatus. Because of existing challenges impeding mass production of graphene, graphene firms are deemed too risky and not profitable enough to attract significant funding. As a result, U.S. firms have made little progress toward scaling graphene production. On the other hand, Beijing's economic and strategic planning drives Chinese research and development. Similar to research into solar technology in the 2000s, Beijing has incentivized graphene mass production research through subsidies, tax cuts, and direct funding.

Silicon Valley and the Lack of Profit Incentives in Graphene Research

Silicon Valley functions through the complex interaction between small, entrepreneurial startup firms and a wide range of economic actors, such as venture capitalist firms, law firms, and consulting firms.[57] Generally, venture capitalist firms act as the crucial bridge between startups and the wider web of Silicon Valley actors. Without this funding, startups cannot afford to connect with the law firms, labs, and consultants necessary to scale production. Moreover, without the approval of reputed venture capitalist firms, Silicon Valley actors may view new startups as too risky to invest in. The importance of venture capitalists in this market is evidenced by the fact that only nine percent of high-tech firms receive venture capitalist funding at the seed stage, but virtually all successful, established firms received venture capitalist funding at that stage.[58]

When considering what startups deserve funding, venture capitalists consider three types of risk: technology risk, entrepreneurial risk, and market risk.[59] As the graphene market stands, technology and market risk are too high to attract venture capitalist funding. Enduring impediments to mass production of graphene impose prohibitive costs to graphene-focused startups. Because of these challenges, graphene products remain confined to small-scale research labs, leaving the market without proof of profitability. Thus, most current research focuses not on practical applications of graphene, but on graphene's scientific principles. As a result, the U.S. research apparatus has not made significant advances toward scalable graphene production and firms that have entered the market with graphene products are small, unprofitable, and liable to collapse.[60]

China's Top-Down Research Advantage

Unlike Washington, Beijing has taken a vested interest in graphene development within China. To this end, it dedicated the Beijing Graphene Institute, partnered with Peking University, to research graphene-related products. Specifically, the institute is focused on mass production technology, as well as on applications of graphene in a wide range of electronic devices.[61] Moreover, in order to encourage industry innovation, Beijing rewards firms that declare new graphene-related patents. Finally, China has invested in a series of foreign graphene-related institutes.[62]

By offering state funding to Chinese firms, Beijing has successfully decreased the risks that would have barred Chinese firms from entering the market. Entry risk in the graphene market is high globally. As previously stated, cost effective methods of mass production have yet to be perfected and the generally small size of firms depresses profit margins even in successful graphene firms. The combination of high risk and low returns, therefore, has proved to be prohibitive to prospective firms in the global graphene market.

China, however, has worked around this challenge by decreasing the risks new firms face, allowing more firms to enter the Chinese graphene market. Beijing's funding has also allowed Chinese firms to lower the price of their products below global market costs.[63] Although the discrepancy between global and Chinese prices is shrinking as technology improves, the gap will persist. As a result, less competitively priced firms around the world are being pushed out of the graphene market.[64]

The Chinese Research Model: Solar Market as Precedent

Chinese activity in the solar market is an instructive parallel to Beijing's maneuvering in the global graphene market. Like graphene, China considered solar power a valuable product for Chinese national interests. To corner the solar market, China used predatory financing to edge out global competition. Through the China Development Bank, Beijing granted billions of dollars in low interest loans to Chinese solar firms, making production easier, cheaper, and less risky.[65] Armed with these loans, Chinese solar firms scaled at unthinkable rates, far outpacing the rest of the industry and excluding foreign competition.[66] In 2006 there were two Chinese companies in a list of the top ten cell producers; in 2010, there were six.[67] There are currently only two non-Asian manufacturers in the top ten, and these companies—First Solar and Q-Cells—have shifted much of their production to Asia.[68]

The key to Beijing's success in taking the solar market did not lie in innovating solar technology, but rather in achieving cheaper mass production of solar products.[69] By mass producing solar technology cheaply, China drove down global solar prices.[70] Beijing increased the effect of this production strategy by directly subsidizing unprofitable firms. For less efficient foreign firms, unbacked by their governments, the new prices were untenable. In this way, Chinese firms were able to weather plummeting prices until global competition dropped from the market.

From Protectionism to Innovation: A Long-Term Solution for U.S. Graphene

> *China's ability to ramp up and overwhelm an industry is unique and particularly devastating with new and emerging technologies, where global competitors may be less established and can be knocked out more easily and quickly.*
>
> -Alan Price, partner at Wiley Rein, 2012[71]

The United States traditionally combats Chinese market manipulation by imposing anti-dumping and countervailing import tariffs. However, tariffs raise domestic industry prices, thereby damaging consumer demand, and leave the United States vulnerable to legal and market retaliation. Moreover, because import tariffs do not improve U.S. manufacturing capacity, they are ineffective in the long run and would fail to curb Chinese domination of the graphene market. Instead of imposing tariffs, the United States should use existing research and manufacturing infrastructure within the Department of Defense to develop cost-effective graphene mass production processes.

The Current U.S. Strategy: Tariffs

Tariffs raise domestic prices and leave the United States vulnerable to retaliation. By targeting import competition, U.S. tariffs decrease U.S. domestic competition. As a result, domestic producers have fewer market incentives to cut costs, allowing them to increase prices.[72] As prices for domestically manufactured goods and imported goods rise, consumer demand decreases.[73] In this way, tariffs may hurt the industry they are meant to protect. Solar producers in the United States, for instance, remain divided over implementing tariffs on Chinese import competitors. Detractors of solar tariffs point out that U.S. demand for solar products is already buffeted by oil and gas energy competition. Producers worry that by raising the costs of solar in the United States, tariffs will only decrease domestic demand further.[74]

In addition to damaging domestic demand, tariffs leave the United States vulnerable to legal and tariff retaliation. Countries facing tariffs on their exports are incentivized to take legal action through the World Trade Organization (WTO), leading to arbitration and dispute counseling.[75] The United States and China, for example, have been engaged in arbitration over solar tariffs since 2012.[76] Whether or not the WTO rules in favor of the plaintiff, or later enforces those rulings, WTO arbitration costs the defendant both time and resources. In addition to legal retaliation through multilateral institutions, targeted countries often implement retaliatory tariffs.[77] Following the current administration's 2016 tariffs on China, which included solar, Beijing responded with a series of tariffs aimed at the president's political base, largely hitting agricultural and manufacturing sectors in electorally important states.[78]

Proponents of tariffs argue that despite domestic pain, these measures act as a counterweight to foreign producers flooding domestic markets.[79] However, tariffs do not effectively improve domestic manufacturing capacity or decrease foreign manufacturing dominance. Instead, import tariffs shelter nascent or struggling domestic industry from foreign competition by decreasing foreign competitor's access to domestic markets. Studies have demonstrated that rather than compelling domestic innovation to close the gap between domestic and foreign manufacturers, import tariffs artificially inflate domestic prices, thereby decreasing incentives for innovation.[80]

In the U.S. solar market, tariffs imposed on Chinese solar importers in 2012 did initially decrease Chinese imports and lead to industry job growth.[81] From 2012 to 2013, Chinese imports declined by 45 percent; however, U.S. manufacturing capabilities did not increase.[82] Instead, industry job growth occurred in the delivery and installation sectors of the solar industry—sectors that have increasingly relied upon importation of cheap Chinese solar parts. Because of this dependence, President Trump's renewed solar import tariffs against China of 2016 led to a sharp decrease of over 17,000 U.S. jobs.[83] Despite Obama and Trump-era tariffs, Chinese solar firms have steadily increased their shares of the global solar market, reaching two-thirds of the global manufacturing capacity in 2017.[84]

Mass Production Research: A Long-Term Solution

Rather than subjecting the U.S. economy to the unnecessary hardships generated by inefficient import tariffs, the United States should invest in direct research into mass production of graphene. Directly incentivizing innovation will allow U.S. graphene producers to close the gap between U.S. and Chinese graphene production. By getting to the root of Chinese domination of the graphene market, mass production research acts as a long-term solution. Moreover, mass production innovation effectively avoids import tariff weaknesses, such as retaliation and domestic price hikes.

While direct government intervention into the private market is not always an ideal solution, there is clear precedent in the realm of national security. The Department of Defense intervened to reestablish mass production of the adenovirus vaccine after the private market stopped production in 1994. In response to a suspected influenza outbreak among U.S. military trainees in 1953, the U.S. Army Medical Center's Department of Respiratory Diseases began an investigation and discovered that adenovirus caused the outbreak. Three years later the Walter Reed Army Institute of Research developed a vaccine against types four and seven of the adenovirus and contracted manufacturing to private U.S. contractors.[85] In the 1990s, when market barriers increased production costs and decreased profit margins, the private contractors ended production of the vaccine. As a result, incidences of adenovirus outbreaks among U.S. troops rose. The U.S. Department of Defense, in order to decrease disease among the troops, awarded funding to re-establish and maintain vaccine manufacturing.[86]

Like Silicon Valley's lack of incentive to research graphene mass production, U.S. private contractors lacked market incentive to maintain production of the adenovirus vaccine in the face of declining profit margins. This lack of private market incentives represented a threat to U.S. national security, prompting government intervention. Finally, like the adenovirus case study, today's U.S. Department of Defense has the infrastructure in place to bridge the gap between U.S. security needs and manufacturing capabilities. The Department of Defense Research and Engineering Enterprise, which encompasses DARPA, the Army, Navy, and Airforce research labs, and the Defense innovation labs, among others, maintains the production and research capacity to innovate graphene mass production. Therefore, the Department of Defense should fund research and development into graphene mass production in order to close the gap between Chinese and U.S. manufacturing capabilities.

Conclusion

Because of its strength and ability to store energy, conduct heat and electricity, filter particles, and stretch, graphene is poised to revolutionize the space and energy industries, armor production, and water desalination. Recent breakthroughs in the mass production of graphene by Chinese-funded firms have positioned China to dominate the emerging market. The United States, meanwhile, is falling further behind.

While China and the United States are close trade partners, the United States cannot afford to rely on China to provide graphene-related products. As a variety of research teams have demonstrated, graphene will lead to longer lasting batteries, more efficient satellites and lasers, lightweight armor, and cost-effective water desalination plants. China's domination of these technologies will enable Beijing to leverage its influence at the expense of the United States. As a result, the United States will face a series of strategic threats in a number of sectors of national security. In light of graphene's importance to U.S. national security, Washington cannot afford to rely on Beijing for graphene.

Despite the potential of graphene, challenges of mass production have impeded industry growth in the United States. As a result, graphene products are not profitable on the market. Because the U.S. research and development apparatus, primarily Silicon Valley, operates through profit, U.S. research firms are not incentivized to research graphene. Chinese graphene firms, on the other hand, are directly funded and subsidized the by Chinese government to develop cost-effective mass production processes. In light of cheaper Chinese mass production of graphene, tariffs will not be enough to curb Chinese dominance in the global graphene market. Instead, the United States should use existing infrastructure within the Department of Defense to develop U.S. mass production of graphene.

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[2] "Graphene Market 2018 Global Analysis, Industry Demand, Trends, Size, Opportunities, Forecast 2023," *MarketWatch,* last modified August 31, 2018, https://www.marketwatch.com/press-release/graphene-market-2018-global-analysis-industry-demand-trends-size-opportunities-forecast-2023-2018-08-31.
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[4] Xu Xinchen and Wang Yao, "Graphene could be key to China's self-made chips," *CGTN,* last updated august 9, 2018, https://news.cgtn.com/news/3d3d514e33517a4d79457a6333566d54/share_p.html.
[5] "What is Graphene?" *Graphene-info: The Graphene Experts,* last modified December 24, 2018, https://www.graphene-info.com/graphene-introduction. And Jesus de La Fuente, "Properties of Graphene," *Graphenea,* https://www.graphenea.com/pages/graphene-properties#.XI2caBNKiqQ. At just one atom thick, graphene weighs 0.77 milligrams per square meter; this is approximately 1000 times lighter than paper.
[6] Xiluan Wang and Gaoquan Shi, "Flexible graphene devices related to energy conversion and storage," *Energy & Environmental Science 3,* (2015). According to this study, graphene's atomic structure "allows graphene sheets to easily deform in the direction normal to their surface, providing them with good flexibility." Graphene sheets are also blended with other materials to form composites with increased flexibility
[7]The conductivity of electrical materials is generally expressed relative to copper. In materials *commonly* used in electrical applications, silver is the only material to surpass copper. However, graphene also performs better than copper, making it a promising material for electrical conductivity. Graphene is also superior to many conductors in that it retains high conductivity at room temperature; other superconductors must undergo expensive cooling treatment to obtain these levels of conductivity. See the following sources for more information. "Electrical Conductivity of Materials," *Blue Sea Systems,* https://www.bluesea.com/resources/108/Electrical_Conductivity_of_Materials. "Graphene: the gold rush that is going to change the world… but when?" *InvestorIntel*, last modified August 26, 2013, https://investorintel.com/sectors/technology-metals/technology-metals-intel/graphene-the-wonder-material-that-is-going-to-change-the-world-but-when/. Elizabeth Gibney, "Surprise graphene discovery could unlock secrets of superconductivity," *Nature,* last modified March 5, 2018, https://www.nature.com/articles/d41586-018-02773-w
[8] "Thermal Management for Space Applications," *Space Tech Expo USA,* http://www.spacetechexpo.com/resources/news-and-editorial/news-container/2017/05/10/thermal-management-for-space-applications. And "Thermal Management of Laser Diodes," *Aerospace & Defense,* last modified August 1, 2016, https://www.aerodefensetech.com/component/content/article/adt/features/articles/25247. According to the Space Tech Expo, thermal management is essential to protect electronics from severe temperature changes that occur in a vacuum environment. These systems are constrained both by weight and volume. Managing temperature stability is also essential to maintain the reliability of lasers and increase the lifetime of powerful laser diodes.
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[31] Trijo Tharayil, Lazarus Godson Asirvatham, Vysakh Ravindran, and Somchai Wongwises, "Thermal performance of miniature loop heat pipe with graphene-water nanofluid," *International Journal of Heat and Mass Transfer* 98, (2016): 957-968. Heat pipes are recognized as one of the best options to cool electronic devices. Miniaturized heat pipes may be necessary as electronics become smaller with larger heat loads. The effectiveness of a heat pipe is dependent on the fluid used within it. Fluids with increased thermal conductivity, such as those with nanoparticles, are promising fluids for heat pipes. The Tharavil paper explores the performance of a graphene-water nanofluid, confirming that graphene particles improved the performance of a miniature heat loop pipe.
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https://cdn.defenseone.com/a/defenseone/interstitial.html?v=8.26.0&rf=https%3A%2F%2Fwww.defenseone.com%2Ftechnology%2F2019%2F02%2Fchina-russia-building-attack-satellites-and-space-lasers-pentagon-report%2F154819%2F. And Patrick Tucker, "Pentagon Intelligence Chief: Russia and China Will Have Weapons in Space 'In the Near Future,'" *Defense One,* last modified June 27, 2018, https://www.defenseone.com/technology/2018/06/pentagon-intelligence-chief-russia-and-china-will-have-weapons-space-near-future/149335/. According to these sources, China is building experimental satellites that have both peaceful and counterspace applications. These sources also note that the 1967 Outer Space Treaty acknowledges "the common interest of all mankind in the progress of the exploration and use of outer space for peaceful purposes." However, the treaty only bans weapons of mass destruction and the use of the moon for non-peaceful purposes. Other weapons are not expressly forbidden.

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[86] Ibid. Adenovirus is not the only case in which the U.S. government has intervened to promote vaccine research. During the Ebola outbreak, the National Institute of Allergy and Infectious Diseases collaborated with the U.S. Army Medical Research Institute of Infectious Diseases and Okairos, a Swiss-Italian biotech company, to develop a vaccine. The Department of Defense also contributed $25.6 million for research and development for the Ebola outbreak; part of this funding was allocated for vaccine research. This intervention again provides precedent for government intervention in the market to promote a technology deemed vital to security. See the following sources for more information. "NIAID/GSK Investigational Ebola Vaccine (cAd3-EBOZ)," *NIH,* last modified February 26, 2016, https://www.niaid.nih.gov/diseases-conditions/ebola-vaccines. And "DOD Helps Fight Ebola in Liberia and West Africa," *U.S. Department of Defense,* http://archive.defense.gov/home/features/2014/1014_ebola/.