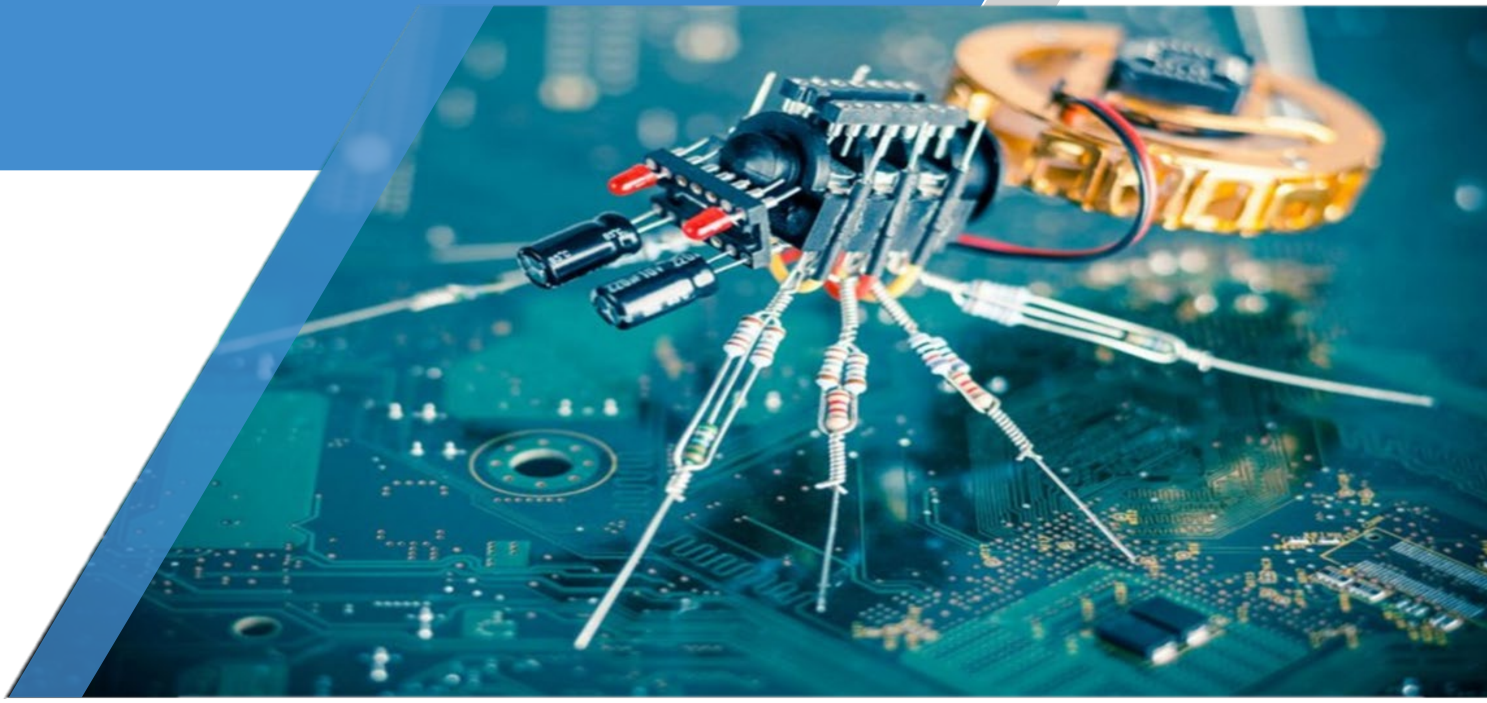
National Nanotechnology Initiative (NNI)

Economic Impact Analysis: 20 Years of Nanotechnology Investments



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Contents

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Executive Summary

Nanotechnology has revolutionized numerous industries across the globe and exists at all levels of the economy, from manufacturing to consumer products. By harnessing the unique properties of materials at the nanoscale, scientists and engineers have developed innovative solutions that enhance the performance, functions, efficiency, and sustainability of nanotechnology products. Nanotechnology has played a vital role in many applications, including enhanced strength and flexibility of materials, reduction of environmental impact, increased fuel efficiency, improved energy generation, storage, and efficiency, and development of targeted drug delivery. This report will examine the novel ways in which nanotechnology is being used and its impact on the U.S. economy.

Many products and applications are enabled by and consist of integrated nanotechnology components; however, there is not a clear consensus on what is considered a core nanotechnology product. As a result, quantifying the economic impact of nanotechnology companies and products is challenging. Given the constraints and data limitations, the research team's estimate of **$20.8 billion,** derived from the Bureau of Labor Statistics (BLS) data, is the conservative estimate for the economic impact of nanotechnology in 2020. This is likely an undercount of the impact of nanotechnology because it includes only companies that self-identify as primarily involved in nanotechnology research and development (R&D). It does not fully capture the broader 'nano-economy' and the various levels of the supply chain that it touches.

Building on this baseline estimate, and using a combination of product and company analyses, an additional estimate was developed to expand the understanding of nanotechnology's economic impact. Focusing primarily on the nanotechnology product categories of 'Core Nano' and 'Nano Tools', and a small number of companies within the 'Nano-enabled' and 'Integrated Nano' product categories, yields an estimate of **$67-83 billion** (2022 corporate revenues). While much higher than the BLS estimate, this number is still moderate given the curated approach. This is highlighted by the fact that aggregated revenues of the select list of nanotechnology companies has reached **close to a trillion dollars over the last two decades** (2002-2022). These estimates provide a starting point but are limited by the project schedule and data availability. As a result, there needs to be a sustained, long-term effort to refine and curate the list of products, companies, and the economic impact of nanotechnology.

From 2001 to 2022, federal investment in nanotechnology through the National Nanotechnology Initiative (NNI) totaled approximately $38 billion. The number of Americans that worked in the nanotechnology sector rose from 17,800 in January 2002 to 29,000 in May 2023, nearly a 63% increase. In 2022, the economic impact amounted to $3.74 billion in wages, and many states have seen significant increases in total wages across their nanotechnology workforces. In the U.S., the average salary for a nanotechnology employee ranges from $61,210 to $128,440, whereas the 2021 median household income in the U.S was $69,717.

Nanotechnology plays a vital role in the US economy currently, enabling innovation and creating significant impact across most sectors and industries, and continued growth is projected for the sector. In addition, it continues to drive innovation in the economy and creates a business ecosystem with wide ranging effects, from high paying and competitive jobs to innovative technological solutions for everyday

problems. Most importantly, perhaps, nanotechnology provides groundbreaking benefits and value to consumers and the public, which has been fueled by government investment and guidance.

Introduction

Background

Office of Science and Technology Policy, NNI Strategy [I]

> *"The aim of the NNI is to move nanotechnology discoveries from the laboratory into new products for commercial and public benefit, encourage more students and teachers to become involved in nanotechnology education, create a skilled workforce and the supporting infrastructure and tools to* ***advance nanotechnology*** *and to* ***support the responsible development*** *of nanotechnology."*

The NNI is a U.S. Government R&D initiative consisting of over 30 Federal departments, independent agencies, and commissions working toward the shared vision of a future in which the ability to understand and control matter at the nanoscale leads to ongoing revolutions in technology and industry that benefit society. The NNI enhances interagency coordination of nanotechnology R&D, supports a shared infrastructure, promotes technology transfer, facilitates commercialization, enables leveraging of resources, and establishes shared goals, priorities, and strategies that complement agency-specific missions and activities.

The NNI initiated this report to analyze the economic impact of federal investment in nanotechnology across the last two decades, 2002-2022. This timeline was selected because the NNI was codified by the 21st Century Nanotechnology Research and Development Act in 2003, and thus the range covers its entire existence. Though not exhaustive, this report examines the impact of public investment, growth and trends of the market, and the evolving understanding and application of nanotechnology in the U.S. It also provides key data for evaluating NNI's ability to fulfill its mission and illustrates NNI's successes to date.

Objectives

The U.S. Government has cumulatively invested roughly $40 billion in nanotechnology R&D over the last twenty years. Accordingly, there is a need to capture investment trends and measure the economic impact of nanotechnology investments to ensure that public funds are contributing to technological advancements, economic growth, and societal benefits for the American public. This economic analysis is not restricted to NNI's funding agencies because NNI collaborates with public and private organizations to shape the nanotechnology industry through activities apart from funding, such as standards development and training. NNI works with these groups across the entire technology development lifecycle, from early-stage fundamentals to application-focused activities. Because of NNI's reach and extensive network of partnerships across the industry, it is best to measure how the field has grown, evolved, and impacted the greater U.S. economy in its entirety.

Nanotechnologies undoubtedly contributed to major advancements across industries that drive the U.S. economy, including energy, transportation, medicine, and consumer electronics. Previous efforts to study the economic impact of nanotechnology were hindered by the breadth of the field and inconsistent definitions of its bounds. Therefore, the methodology established herein attempts to gain consensus across the nanotechnology community on the definition of nanotechnology and related categories, and whether to include or exclude specific products and technologies.

Nanotechnology

Overview and Definition

Nanotechnology is the understanding and control of matter at a size scale – often but not limited to the nanoscale (1-100 nanometers) – where unique physical, chemical, mechanical, and optical properties of materials enable novel applications.

The applications and impacts of technology operating at the nanoscale and leveraging nanoscale phenomena are observed across nearly every industrial sector, including medicine, energy, electronics, agriculture, quantum computing, and more. Specific examples demonstrating the breadth of the field are described in the Annual NNI Supplements to the President's Budget[1] and illustrated in this report.

For this economic impact report, the research team reviewed several definitions of nanotechnology from reputable sources lead R&D in nanotechnology and developed an operational definition for the purposes of the research:

> Nanotechnology, n. – *The study, measurement, and manipulation of matter at or near the nanoscale to achieve special properties, functions, or effects only achievable at the nanoscale.*

Though the definitions varied, core similarities across definitions informed the working definition above. In addition, the context surrounding the scientific and industrial definitions of nanotechnology was developed using interviews with subject matter experts, scientific research reports, market reports, journal and news articles, and a review of publications from industry trade groups. The research team developed the operational definition above using the following sources:

> United States Code – Title 15 Commerce and Trade[2]:
>
> "The science and technology that will enable one to understand, measure, manipulate, and manufacture at the atomic, molecular, and supramolecular levels, aimed at creating materials, devices, and systems with fundamentally new molecular organization, properties, and functions."
>
> National Nanotechnology Initiative[3]:
>
> "Nanotechnology is the understanding and control of matter at the nanoscale, at dimensions between approximately 1 and 100 nanometers, where unique phenomena enable novel applications...Nanotechnology research and development involves imaging, measuring, modeling, and manipulating matter between approximately 1–100 nanometers."

[1] National Nanotechnology Initiative. "NNI Budget Supplements and Strategic Plans." Published February 03, 2023. https://www.nano.gov/NNIBudgetSupplementsandStrategicPlans.

[2] The Office of Law Revision Counsel, U.S. House of Representatives via the Government Printing Office. "United States Code, 2018 Edition, Title 15 - COMMERCE AND TRADE, 2018." Published 2018. https://www.govinfo.gov/app/details/USCODE-2018-title15/summary.

[3] National Nanotechnology Initiative. "About Nanotechnology." https://www.nano.gov/about-nanotechnology

International Organization for Standardization (ISO)[4]:

"Application of scientific knowledge to manipulate and control matter in the nanoscale (size range from approximately 1 nm to 100 nm) to make use of size- and structure-dependent properties and phenomena, as distinct from those associated with individual atoms or molecules or with bulk materials"

European Commission Scientific Committee on Emerging and Newly Identified Health Risks[5]:

"Those areas of science and engineering where phenomena that take place at dimensions in the nanometre scale are utilised in the design, characterisation, production and application of materials, structures, devices and systems."

U.S. Patent and Trademark Office[6]:

"i. Nanostructure and chemical compositions of nanostructure; ii. Device that includes at least one nanostructure; iii. Mathematical algorithms, e.g., computer software, etc., specifically adapted for modeling configurations or properties of nanostructure; iv. Methods or apparatus for making, detecting, analyzing, or treating nanostructure; and v. Specified particular uses of nanostructure...(the term 'nanostructure' is defined to mean an atomic, molecular, or macromolecular structure that: [a] Has at least one physical dimension of approximately 1-100 nanometers; and [b] Possesses a special property, provides a special function, or produces a special effect that is uniquely attributable to the structures nanoscale physical size.) "

Key Product Groups and Industry Applications

In this section, we explore the profound impact of nanotechnology in various sectors and industries. Though not exhaustive, this list aims to present a representative sample of nanotechnologies and relevant applications in the following areas: Adhesives, Aerospace, Agriculture, Automotive, Catalysis, Cosmetics and Personal Care Products, Electronics, Energy, Environmental Restoration, Healthcare and Medicine/Pharmaceuticals, Lubricants, Oil and Gas, Semiconductors, and Textiles and Fabrics. Due to the crosscutting nature of nanotechnology applications, these categories are not exclusive. For example, nanocoatings are widely used in multiple industries and thus show up multiple times in the following vignettes but have industry-specific applications and effects. Additionally, companies and products were included or excluded based on the definition and criteria established in this study, and not every company mentioned in this section was ultimately included (see the section Economic Impact Analysis for specific criteria for inclusion and exclusion established by the research team).

Note – The footnote citations in this section, Key Product Groups and Industry Applications, have been consolidated in Appendix B – Nanotechnology Company Citations to improve readability.

[4] International Organization for Standardization. "Nanotechnologies — Vocabulary — Part 1: Core terms." https://www.iso.org/obp/ui/#iso:std:iso:ts:80004:-1:ed-1:v1:en
[5] European Commission Scientific Committee on Emerging and Newly Identifies Health Risks. "Nanotechnologies." https://ec.europa.eu/health/scientific_committees/opinions_layman/en/nanotechnologies/index.htm#il1
[6] United States Patent and Trademark Office. "CLASS 977, NANOTECHNOLOGY." https://www.uspto.gov/web/patents/classification/uspc977/defs977.htm

Adhesives

Companies in the adhesives sector revolutionized the way materials bond and have developed innovative, stronger, and more durable adhesives by harnessing unique properties at the nanoscale. One prominent example is the use of nanoscale particles to enhance the adhesive strength and flexibility of various bonding agents. Nanoparticles such as silica, carbon nanotubes, and graphene have been incorporated into adhesive formulations, creating adhesives with superior mechanical properties. These nanocomposite adhesives are used in industries ranging from automotive to aerospace, where they provide improved resistance to temperature fluctuations, moisture, and physical stress. Nanotechnology enabled the development of pressure-sensitive adhesives, finding use in medical applications such as wound dressings and transdermal drug delivery patches.

Several firms are actively involved in leveraging nanotechnology in the adhesive sector. For instance, **3M**[7] utilized nanotechnology to develop advanced adhesives that have been employed in electronics, automotive, and medical applications[8]. Other US companies are also researching[9] and developing nanotechnology-based adhesives, continuously pushing the boundaries of adhesive technology.

Aerospace

The unique properties of nanomaterials enable the development of lightweight and high-strength components, leading to improved fuel efficiency and reduced emissions across the Aerospace industry. For instance, nanotechnology is used to construct lighter and stronger airframe structures, like those seen in **Zyvex Technologies'**[10] Arovex™ prepreg composites that incorporate carbon nanotubes and graphene to enhance their performance. Additionally, nanotechnology has been employed to develop advanced coatings that provide improved resistance to extreme temperatures, corrosion, pressure, and wear, ensuring longer lifespans for aerospace components.

Nanotechnology has influenced the development of advanced sensors and nanoelectronics, enabling more accurate measurements and diagnostics, and real-time monitoring of craft health and performance, leading to safer and more reliable flights. In the U.S., **Boeing**[11] and **Honeywell Aerospace**[12] are at the forefront of integrating nanotechnology into the aerospace sector.

Agriculture

Within the agriculture space, leveraging nanoscale materials and techniques has allowed practices to become more efficient, sustainable, and environmentally friendly. Nanoparticle-based fertilizers and pesticides allow for the controlled release of nutrients and active ingredients, which enhances nutrient uptake by plants and improves crop protection. Additionally, nanosensors and nanoscale imaging technologies enable real-time monitoring of soil conditions, plant health, and pest infestations to empower farmers to make decisions that optimize the use of limited resources.

Several US companies participate in developing and implementing nanotechnology-based solutions in agriculture. One notable example is **Monsanto**[13] (now part of Bayer), whose R&D investments have led to the creation of nanoparticle-based crop protection products that target pesticide delivery. These products reduce environmental impact and safeguard crops. **Standard BioTools**[14], a biological research equipment manufacturer, produces sensors that enable farmers to apply resources precisely where and when needed.

Automotive

One of the key areas where nanotechnology's impact can be seen is in automotive materials development. Nanocomposites are used to manufacture lighter and stronger components, which improves fuel efficiency and safety for occupants. Moreover, nanocoatings with self-cleaning and scratch-resistant properties ensure long-lasting and aesthetically pleasing appearances to car surfaces. Furthermore, nanosensors are critical to automatic parking and automatic driving functions found in the most innovative automobiles. Nanotechnology is instrumental in the electronics industry (explained in detail below), and, increasingly, most vehicles depend on the inclusion of advanced electronics for both functionality and product differentiation.

Sila Nano[15], founded by a former Tesla lead engineer, utilizes nanotechnology in their automotive batteries to enhance charge and discharge rates, leading to quicker charging times and improved overall performance. **Ford[16]** enhances their vehicles' structural integrity while reducing weight with nanotechnology-based solutions, leading to better energy efficiency and handling.

Catalysis

A major area of development has been the use of nanotechnologies in catalysis, shaping the way chemical reactions are facilitated and speeding up numerous industrial processes. Nanoscale catalysts dramatically increase the surface area for chemical interactions to enhance catalytic activity and selectivity. Nanocatalysts are used in various industries, including petrochemicals, pharmaceuticals, and environmental remediation. In the petroleum refining industry, nanotechnology has improved the efficiency of processes, including hydrocracking and hydrotreating, and led to cleaner and more efficient end products. Nanocatalysts also played a critical role in pharmaceutical synthesis, enabling more precise and sustainable chemical transformations in drug manufacturing.

Several US firms are active in the catalysis space, including **Hyperion Catalysis International, Inc**.[17], which fuses carbon nanotubes to form strong, highly porous, open-cell structures that support precious-metal refinement and electronics applications. **Zeolyst[18]** uses nanotechnology in the production of nanoscale zeolite powders, which assist petrochemical refining, emissions control, and environmental catalysis.

Cosmetics and Personal Care Products

Nanotechnology has enabled innovative products with improved delivery, enhanced performance, and safety across the cosmetics and personal care products sector. Nanoscale emulsions and nanocarriers are used in skincare ingredients, enabling better penetration into the skin, and enhanced therapeutic outcomes. For example, nanoparticles of hyaluronic acid and ceramides are incorporated into many moisturizers and skin care products, providing deeper hydration and promoting skin cell repair and replacement. Additionally, use of nanoparticles, zinc oxide and titanium dioxide, resulted in the development of sunscreens with transparent and more effective UV protection.

Several cosmetic and personal care product companies have embraced nanotechnology to develop cutting-edge applications. **L'Oréal Group**[19], one of the world's largest cosmetic firms with extensive operations in the US, has extensively explored nanotechnology applications in their products. As an example, they utilized nanocapsules in their skincare and haircare products, allowing for targeted delivery of specific ingredients for better performance and effectiveness. **Estée Lauder**[20] similarly incorporated nanotechnology into their products, creating advanced anti-aging products with active ingredients that operate at the nanoscale. Moreover, companies like **Dow Chemical**[21] and **Procter & Gamble**[22] have heavily invested in nanotechnology research to improve their cosmetic and personal care offerings.

Electronics

Nanotechnology's impact on the electronics sector has been transformative, and there is a vast range of applications to propel the development of smaller, faster, and more efficient electronic devices. The most prominent example of electronic applications is the use of nanomaterials and nanotechnology in the production of transistors and semiconductors, for which a dedicated section is included later in this list. Certain nanomaterials possess exceptional electrical properties, allowing for the creation of high-performance and energy-efficient electronic circuits throughout the sector. Nanotechnology is integral in electronic packaging, casing, and cooling solutions, enabling enhanced thermal conductivity and heat dissipation.

With the integration of quantum dots into displays to achieve better color accuracy and energy efficiency, nanotechnology has certainly facilitated transformative advancements in display and optic technology. Quantum dots deeply penetrated the electronic goods market and exist in everything from Smart Devices to digital billboards. These materials are used in optoelectronic devices, like quantum dot lasers and light-emitting diodes (LEDs), which enable efficient emission and manipulation of light at the nanoscale.

The development of nanoelectromechanical systems (NEMS) and nanophotonics, where nanoscale components are integrated into semiconductor devices, enabled novel functionalities. NEMS devices, such as nanoscale sensors and actuators, and nanophotonics open new possibilities in optical communications and computing. Companies like **Intel**[23], **IBM**[24], and **Samsung**[25] are at the forefront of incorporating nanotechnology into design and manufacturing of advanced optical devices used in computing, semiconductors, displays, and more.

Nanosys[26] is a leading producers of quantum dots within the U.S., and their technology helps bring crisper, more detailed, and more energy-efficient displays to customers.

Energy and Sustainability

Nanotechnology's presence within the energy and sustainability space is quite radical, offering innovative solutions to improve energy generation, storage, and efficiency. For example, in solar energy, nanomaterials like quantum dots and nanowires are incorporated into solar cells to enhance light absorption and increase energy conversion efficiency. Nanotechnology has also allowed producers like

Indium Corporation[27] to make more lightweight and flexible solar panels, transforming conditions in which solar energy generation can be conducted.

Additionally, nanotechnology has been instrumental in improving energy storage technologies. Nanoscale materials, such as graphene and lithium-ion nanocomposites, contribute to higher-capacity and faster-charging batteries, revolutionizing energy storage. Firms like **Group14**[28], with nanotechnology-enabled batteries, have played a crucial role in advancing energy storage technologies. **Altairnano**[29] also uses nanomaterials for energy storage and power delivery applications.

Furthermore, commercial materials throughout the construction industry employ nanotechnology to create more sustainable buildings equipped with energy-efficient lighting, coatings that prevent materials from leeching into the atmosphere when exposed to sunlight, and energy and temperature-efficient construction materials for buildings.

Environmental Restoration

Nanotechnology transformed environmental restoration efforts by employing innovative solutions that enhanced capabilities in water purification, air pollution clean-up, and soil remediation. For example, nanoscale zero-valent iron (nZVI) particles remove contaminants from groundwater by breaking down harmful pollutants into non-toxic substances. Firms like **Membrane Technology and Research, Inc.**[30] use nanotechnology to develop nanofilters and nanomembranes that efficiently remove heavy metals, organic pollutants, and microorganisms from water sources and aquifers. Nanotechnology is also involved in the development of many advanced sensors, like those developed by **Nevada Nano**[31] that monitor pollutants and emissions. Firms like **BASF**[32]**, DuPont**[33]**,** and **Vader Nanotechnologies**[34] are actively involved in development and commercialization of nanotechnology-enabled solutions for environmental restoration.

Healthcare and Medicine/Pharmaceuticals

Perhaps some of the most promising industrial applications of nanotechnology are within the healthcare, medicine, and pharmaceuticals industries. Numerous firms are actively involved in the development and commercialization of nanotechnology-enabled healthcare products. For example, nanotechnology has made notable contributions in targeted drug delivery. Nanoscale drug carriers, such as liposomes and nanoparticles, can deliver medications directly to specific cells or tissues, improving drug efficacy while reducing side effects. For example, **Bristol-Myers Squibb Company**[35] produces Abraxane, a nanoparticle-based chemotherapy drug used to treat breast, lung, and pancreatic cancer, which has demonstrated enhanced drug delivery capabilities and improved patient outcomes.

Within diagnostics, nanotechnology enabled the development of sensitive and specific nanosensors for early disease detection. **Cardea Bio, Inc.**[36] produces nanoscale biosensors that can detect disease biomarkers at low concentrations, allowing for quicker and more accurate diagnoses. Additionally, nanoparticles are used to enhance medical imaging techniques like magnetic resonance imaging (MRI) and computed tomography (CT).

Regenerative medicine producer **BioHeart, Inc**.[37] leverages nanomaterials, such as nanofibers and nanoscaffolds, to advance tissue regeneration and repair. These materials mimic the natural structures found within cells to promote cell growth, making them valuable tools in tissue engineering and regenerative therapies in cardiovascular healthcare.

The biotechnology company **Illumina[38]** uses nanotechnology in their gene sequencing platforms to analyze DNA at the nanoscale and enable rapid and cost-effective genetic testing. Further, **Gilead Sciences[39]**, one of many firms using nanotechnology in the battle against COVID-19, developed a nanotechnology-based antiviral drug, Veklury (remdesivir), that was approved for the treatment of COVID-19 by the FDA in 2020. Many of the mRNA COVID-19 vaccines, including those produced by **Pfizer[40]** and **Moderna[41],** use nanotechnology to stimulate an immune response against COVID-19. The vaccines use lipid nanoparticles to preserve, stabilize, and direct the uptake of mRNA in targeted cells enabling the body's immune system to recognize and fight viruses earlier.

Lubricants

By incorporating nanotechnology, nanoscale additives, and engineered nanoparticles into lubricant formulations, companies can enhance lubricant properties, reduce friction, and increase wear resistance. One crucial application of nanotechnology in lubricants is the use of nanoparticles like graphene, molybdenum disulfide, and nanodiamonds as 'solid' lubricants. They form protective layers on the surfaces in contact, reducing friction, and preventing metal-to-metal contact, thus extending the lifespan of machinery, and reducing maintenance costs.

Nanotechnology allowed for the creation of lubricants with self-repairing properties, where nanoparticles fill in surface defects and microcracks, ultimately improving performance and service life of machines while reducing the risk of mechanical failures. Moreover, the addition of nanoscale additives in lubricants has enabled better thermal and oxidative stability, making them suitable for high-temperature and extreme operating conditions.

Companies including **Castrol[42], ExxonMobil[43],** and **Shell[44]** have been actively involved in developing nanotechnology-enabled lubricants. These industry leaders are at the forefront of integrating nanotechnology advancements into their lubricant products, providing customers with high-performance lubricants that contribute to increased equipment durability and energy conservation.

Oil and Gas

Nanotechnology revolutionized exploration, production, and refinement processes in the oil and gas industry. Companies like **Shell[45]** and **BP[46]** are actively exploring nanotechnology-based enhanced oil recovery (EOR) methods to maximize oil extraction. In this process, nanoparticles, including nanoscale surfactants and nanofluids, improve the displacement of oil from reservoirs and increase overall oil production. These nanoparticles alter the interfacial properties between oil and water to enable better oil recovery.

Another crucial application of nanotechnology is in drilling and well completion. **Haliburton**[47] uses nanomaterials to enhance drilling mud properties to reduce friction and wear during drilling operations. Nanotechnology also contributes to the development of 'smart' drilling fluids with nanoparticles that can detect and seal fractures in wellbores, preventing fluid loss from wells.

As mentioned in the catalysis section, nanotechnology plays a role in refining and downstream processes where catalysts with nanoscale structures increase the yields of valuable products from crude oil. These catalysts can selectively break down large hydrocarbon molecules into more valuable fuels and petrochemicals, which are increasingly used by oil producers and refiners such as **Exxon Mobil**[43]**.**

Transistors and Semiconductors

Within the development of advanced transistors and semiconductors, size is a critical limiting factor for high-tech devices. As traditional transistors have shrunk, they have faced challenges from power leakage and heat dissipation at the nanometer scales. Nanotechnology enabled the creation of nanoscale transistors that use materials like carbon nanotubes, graphene, and semiconductor nanowires. These nanoscale transistors offer improved performance over traditional transistors, with reduced power consumption, making them ideal for cutting-edge, high-speed, and future applications in electronic devices. Companies like **Coventor, Inc.**[48] are actively researching and applying nanotechnology in the transistor space.

Modern day semiconductors would not exist without nanotechnology. Nanofabrication techniques, like photolithography, atomic layer deposition, and molecular beam epitaxy, enable the precise placement of atoms and molecules, allowing for the creation of integral semiconductor structures and components. Nanotechnology enables the further miniaturization of advanced semiconductors, allowing for precise control over material properties at the nanoscale, and the development of components with reduced size dimensions, while retaining or improving performance. Firms like **Nagase ChemteX America LLC**[49] **and Semicore Equipment, Inc.**[50] produce equipment that enables thin-film deposition and other semiconductor manufacturing practices. **SkyWater Technology**[51] leads the growth and development of America's domestic semiconductor manufacturing industry – in support of the recent CHIPS and Science Act of 2022[52] and the increasing need for America to compete globally in the semiconductor space.

Phase-change memory (PCM) utilizes nanoscale materials that switch between amorphous and crystalline states to store information, which demonstrates the impact of nanotechnology on the semiconductor and transistor space. PCM offers a promising alternative to traditional flash memory, with applications in computing systems. These technologies rely on nanoscale structures to store and manipulate data. Like their work with NEMs and nanophotonoic devices, firms like **IBM**[53] and **Samsung**[54] are currently researching, developing, and implementing Nanotechnology-enabled PCM solutions in their computing and electronics products to transition electronic devices from standard RAM and flash to a much faster and more reliable type of storage.

Textiles and Fabrics

Nanoscale materials and nano-fabrication techniques are integrated into modern-day textiles, offering a wide range of benefits, from improved durability and stain resistance to enhanced UV protection and antimicrobial properties. One of the prominent applications of nanotechnology in textiles is the development of nanocoatings. Nanoscale coatings, such as nanoparticles of titanium dioxide or zinc oxide, can be applied to fabrics to make them more resistant to stains, water, and UV radiation. They create a protective layer on the fabric's surface without altering its appearance or breathability. Nanotechnology enabled ‘self-cleaning’ textiles that repel dirt and liquids. Nanomaterials with superhydrophobic or oleophobic properties create fabrics that are resistant to water and oil-based stains. Firms like **Nano-Tex**[55] and **Schoeller Technologies**[56] supported the development and commercialization of these products.

Nanotechnology is not limited to fabrics that are worn, as can be seen with nanofibers. Nanofibers are ultrafine fibers with diameters on the nanometer scale, offering exceptional properties like high surface area, breathability, and flexibility. These fibers find applications in filtration, wound dressings, and air and water purification. **Donaldson Company**[57] and **Hollingsworth & Vose**[58]**,** for example, use nanofiber technologies in filtration applications to improve air and liquid filtration efficiency.

Economic Impact Analysis

Methodology

Throughout the research and development of this report, the approach and methodology evolved as new information was discovered and constraints or limitations were encountered, but these three phases below remained consistent throughout. The team developed parallel, or complementary, estimates to examine and detail various elements and aspects of the nanotechnology economy. This included types and numbers of companies, categories of products they create, industries and areas they operate within, number of people they employ, revenues they report, locations of their operations, and more.

Our methodology (described below) is based on a bottom-up approach and on addressing the concern of identifying the economic impact of nanotechnology, as opposed to the larger, but challenging to identify, impact of nano-enabled commerce. The research team divided the project into three phases:

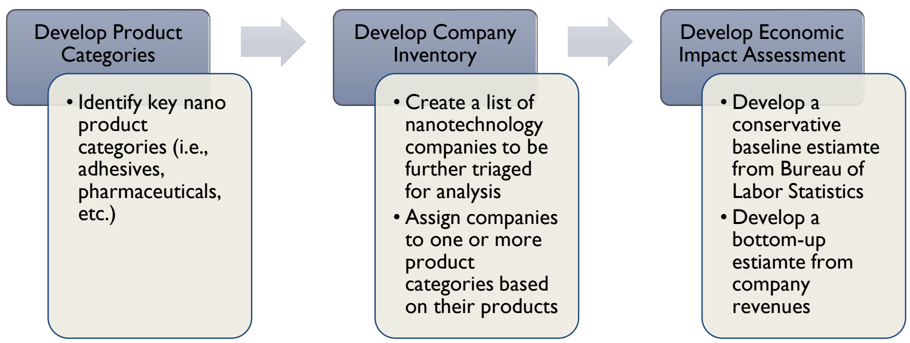

FIGURE 1: METHODOLOGY

Assumptions and Constraints

Throughout the research and development of the report, the research team encountered several challenges including:

- A lack of consensus on a definition of "nanotechnology" and "nano-enabled products" for determining economic impact.
- While there is a NAICS code (541713) – Nanotechnology Research and Development (R&D), there are not complementary codes present to cover the full breadth and depth of the nanotechnology economy, subsectors, and products, and, as a result, using NAICS codes alone undercounts the firms active in the space.
- Revenues for private companies are often not available and the limited data identified poses constraints, as it is not collected or validated by an official organization like the Bureau of Labor Statistics or the Census Bureau.
- Many companies do not readily disclose or identify the use of nanotechnology in their products for several reasons, including for regulatory and insurance purposes and/or because of the perceived risk some consumers may associate with the phrase[59]. Items that the scientific and

[59] CRO Forum. "Emerging Risks Initative – Major Trends and Emerging Risk Radar 2022 Update" Allianz. https://commercial.allianz.com/news-and-insights/reports/emerging-risks-initiative-cro-forum-2022.html

research community consider to be nanotechnology, dependent upon nanotechnology, or resulting from the inclusion or use of nanotechnology are often not explicitly called nanotechnology. In a few cases, products that do not contain any nanotechnology include "nano" labels as a prefix. As a result, a comprehensive list of nanotechnology products does not readily exist and determining what or how much of a role nanotechnology plays in a particular product is challenging.

- Many companies with product portfolios that extend beyond nanotechnology often do not identify the revenues exclusively associated with nanotechnology, or attributable directly to their nanotechnology products or lines of business.
- Research estimates of the nanotechnology market vary widely and there is no clear consensus.
- Initial estimates provided through this project will need follow-up analysis to become more precise but can serve as a foundation from which the broader nano research community can build.

Key Guiding Principles

In response to these constraints, the study team developed the following guiding principles to inform the project:

- Develop multiple estimates utilizing different approaches, including a conservative, defensible baseline based upon best practice in economics.
- Avoid the use of non-economic concepts (ex: multipliers or ascribing rough percentages for a subset of nano-products within a larger firm) as they are imprecise, subjective, and lead to a less reliable estimate.
- Balance the level of effort and focus on high-level approaches, as nanotechnology is an incredibly complex topic.
    - Example: Develop a repository of products that covers most nanotechnology products, understanding that niche products or developing areas that are not at scale may be excluded from analysis.
- Focus on developing a rough order of magnitude as a starting point that can be refined over time. Understand that because of data limitations, estimates may be an undercount of the actual economic impact of nanotechnology.

Phase I: Define Product Categories

As highlighted earlier, this report recognizes that there are many definitions for nanotechnology and, similarly, many avenues that can be used to categorize nanotechnology. The research team developed the following definitions to categorize and value nanotechnology materials and products for this analysis. These product categories were used in the development of the Nanotechnology Product Categorization Repository (see Appendix A) which was in turn used to identify specific nano products and the companies that produce them across the industry.

Nanotechnology Product Categories

Category	Definition	Examples
Core Nano	Purposefully engineered materials, with dimensions close to 100 nanometers (nm) or smaller that have been minimally processed.	Graphene, quantum dots, carbon nanotubes, nanoporous materials, nanostructured metals, nanowires, nanofluids

Nano-tools	Nanotechnology-based tools that are used to manufacture materials and products or conduct nanotechnology research.	Scanning tunneling microscopes molecular beam epitaxy (MBE), atomic layer deposition (ALD), nano electrospray ionization technology, nano etching tools, Nanoscale metrology tools
Integrated Nano	Products for which nanotechnology is critical to the functionality of the product and/or the product functions at the nanoscale. Products that cannot function without nanotechnology.	mRNA vaccines, hard disk drives (HDD), nano-based drug delivery carriers, semiconductors, Nano-tape
Nano-enabled	Finished goods whose performance is significantly improved by nanotechnology materials, components, and/or nano-enabled manufacturing processes	Pharmaceuticals, capacitors, automobiles, aircraft and spacecraft, power tools, sporting goods, fuel additives, sunscreen, agricultural disease sensors, anti-microbial textiles

To develop these product categories, the research team began with a Value Chain Analysis informed by the work of Dr. Stacey Frederick, a professor at Duke University and a researcher examining the nano-economy with the University of California Santa Barbara's Center for Nanotechnology in Society.

Center for Nanotechnology in Society, Dr. Stacey Frederick [60]

Value chain is "a structure that can be used to categorize, organize, and visualize the activities, places, and firms involved in making a product (or service). It includes the full range of activities involved in the process of taking an idea from innovation through commercialization. This includes activities related to production and transportation (supply chain), as well as other value-adding activities such as research, design, marketing, and support services."

Through the Value Chain Analysis, the team identified products at all levels throughout the 'nano-economy' beginning with nanomaterials moving to intermediate products, and finally finished products in the marketplace. The value chain analysis informed product categorizations, as the value chain approach helped ensure products and firms were not errantly excluded, while the categories helped to differentiate products and curate the list of firms included in the analysis.

Each product was designated as one of the four established categories. This list was used to identify firms in the nano-economy by examining their primary products. If a company produced multiple products, it was only included in the economic analysis if most of their products were nanotechnology products, or if the firm identified itself as a nanotechnology firm. Many large firms that do have operations and products

[60]Stacey Frederick. "California in the nano economy, Global Value Chains Center." https://www.globalvaluechains.org/cggclisting/california-in-the-nano-economy/

in the nanotechnology space are excluded from the economic analysis because specific breakdowns for their product lines are not available and the company inventory analysis is scoped to focus exclusively nanotechnology products and firms. As a result, the estimates in this report are conservative.

The research team populated the Nanotechnology Product Categorization Repository by following the below steps:

1. Develop a robust list of products and product groupings.
    a. Products or groupings throughout numerous industries were identified using external market research reports, online nanotechnology inventories, nanotechnology industry associations, and input from subject matter experts.
    b. Examined descriptions of each product or grouping, including the use of nanotechnology in the development of the product.
    c. A concise list of sample firms involved in the research, production, or management of each product or grouping was identified.
    d. The respective industries each product or grouping represents were also identified.
2. Sort products into categories.
    a. Approximated which of the four categories developed each product falls into.
    b. Provided a narrative justification for why the category was selected.
    c. Flagged products that require further investigation and/or validation from Subject Matter Experts, if possible.
3. Review the list and revise.
    a. The research team shared the list with industry experts for review.
    b. The review identified gaps in the product list, provided justification for categorization, and illuminated additional products that should be included.
    c. Made appropriate adjustments to the product repository.
4. Apply Product Categories to identify companies for economic analysis.
    a. Using the repository, the appropriate categorical classification was applied to develop a company inventory based on the products identified for each firm.

Though these categories are not exhaustive, they provide the framework for identifying and grouping nanotechnology products and the firms producing them. These four categories enabled the research team to distinguish between products that count towards the economic impact of nanotechnology while maintaining a high-level approach that ensured relevant producers were not excluded from the analysis.

Phase 2: Develop a Nanotechnology Company Inventory

The economic impact analysis of nanotechnology is an outcome of intensive market research, guided by the assumptions outlined in the previous section. The methodology allowed the research team the flexibility to refine definitions and the approach on an ongoing basis, based on additional research and/or feedback from subject matter experts (SME) in the field. SMEs from academia and industry validated the research and analysis throughout this process – though in a limited manner given the constraints in the project schedule. This helped the team improve the methodology and findings on an iterative basis and establish consensus on the total economic impact.

Generate Inventory of Refined Nanotechnology Companies

As a starting point, the research team developed a list of companies participating in the integration and/or commercialization of nanotechnology to inform the economic impact analysis. Given the lack of clear definitions and cross-sector industry linkages, the list was populated through a parallel approach that considered both consumers and markets:

1. Direct:
   - Research using relevant keywords and topics
   - Apply filters (ex: a combination of primary NAICS codes (541713) and secondary, adjacent NAICS codes)
2. Indirect:
   - Related links and sources (intellectual property applications, cross-sector industry associations, business intelligence/competitor analysis, patent submissions, company news, annual filings, statements, references, citations, etc.)
   - Cross-sector connections (ex: company partnerships, joint ventures)
   - Following the money (ex: private equity/venture investing, government funding, IPOs, etc.)

Research sources included, but were not limited to, the following:

- Targeted online search
- Private Equity and Venture Investments
- Trade Publications and Reports
- Industry and Market Research Databases
- Federal funding
- Trade and Professional Associations
- Tradeshows and Conferences
- Interviews with Subject Matter Experts (SMEs)
- Interviews with Government program staff
- U.S. Patent Office Records
- Members of Nanotechnology standards organizations

The company inventory was revisited regularly to triage the list, creating a list of companies that stakeholders consider valid and complete. Criteria used to triage the list is below:

- Does the description and/or products indicate nanotechnology, nanomaterials, or nano processes? [If no, exclude.]
- Is the firm a subsidy or an acquisition of another firm? [If yes, determine if statistics are available for the segment. If not, exclude.]
- Is the firm publicly traded? [If yes, revenue and employees are available in SEC filings. If no, answer below.]
- For large firms, are revenue estimates available for specific nanotechnology products and the US region? [If no, exclude.]
- Are employee/workforce estimates available? [If no, mark for further investigation.]
- For internationally located firms, are portions of the firm's ownership or operations located overseas, such that all of the revenue or employees cannot be accrued to the United States? [If no, exclude]

Criteria for Inclusion and Exclusion

As a baseline, the company inventory included all core nano and nano-tool firms. To guide the inclusion or exclusion of certain firms due to availability of data, the following criteria dictated when nano-enabled and integrated nano companies were to be included, as the definitions are generic and could include thousands of companies. This, in turn, could significantly increase the revenues included in the economic impact assessment. The table below provides a description of the criteria and indicators, recognizing it can be subjective.

Criteria	Description
Company	• Does the company describe itself as a "nanotechnology" company? • How has the company positioned itself in the market?
Product	• Do products align with one or more product categories, and do nano products constitute a large portion of its product portfolio? • Is nanotechnology a core or enabling technology for the company's products? • Does the company have several patents on nanotechnology – supported by news articles, USPTO data, or research reports?
External View	• How do industry and other external entities view the company and its products? • Is the company included in several nanotechnology investors lists? • Is the company included in news, research reports, and articles that describe the nanotechnology market and products?

Since one of the primary objectives was to develop a reasonable estimate, and based on the exclusion criteria identified above, many firms were not included in the final economic estimate. For example, many large firms with significant revenues were excluded because data for the combination of their individual nanotechnology product segments and US regional revenues were not publicly available, including many firms identified in the Key Product Groups and Industry Applications section found earlier in this report.

Phase 3: Develop an Economic Impact Analysis

General Landscape – Nanotechnology Establishments

Background

The North American Industry Classification System (NAICS) code for the nanotechnology sector was established in 2017. The Bureau of Labor Statistics (BLS) was able to backdate industry data to 1990 by using pre-existing data and identifying firms that eventually ended up in the 2017 NAICS code.

BLS uses the term "establishments," which are business entities in a single physical location where one predominant activity occurs. This is similar to, though different, from the term "firm", which can be comprised of multiple establishments[61]. For example, if there are 10 gas stations in a town owned by 6 proprietors or firms, economic analysis is primarily concerned with the number of locations (10), not the number of corporate firms that may own them (6).

[61] US Bureau of Labor Statistics Monthly Labor Review. "Establishment, firm, or enterprise: does the unit of analysis matter?" https://www.bls.gov/opub/mlr/2016/article/establishment-firm-or-enterprise.htm#:~:text=An%20establishment%20is%20a%20single,Internal%20Revenue%20Service%20(IRS).

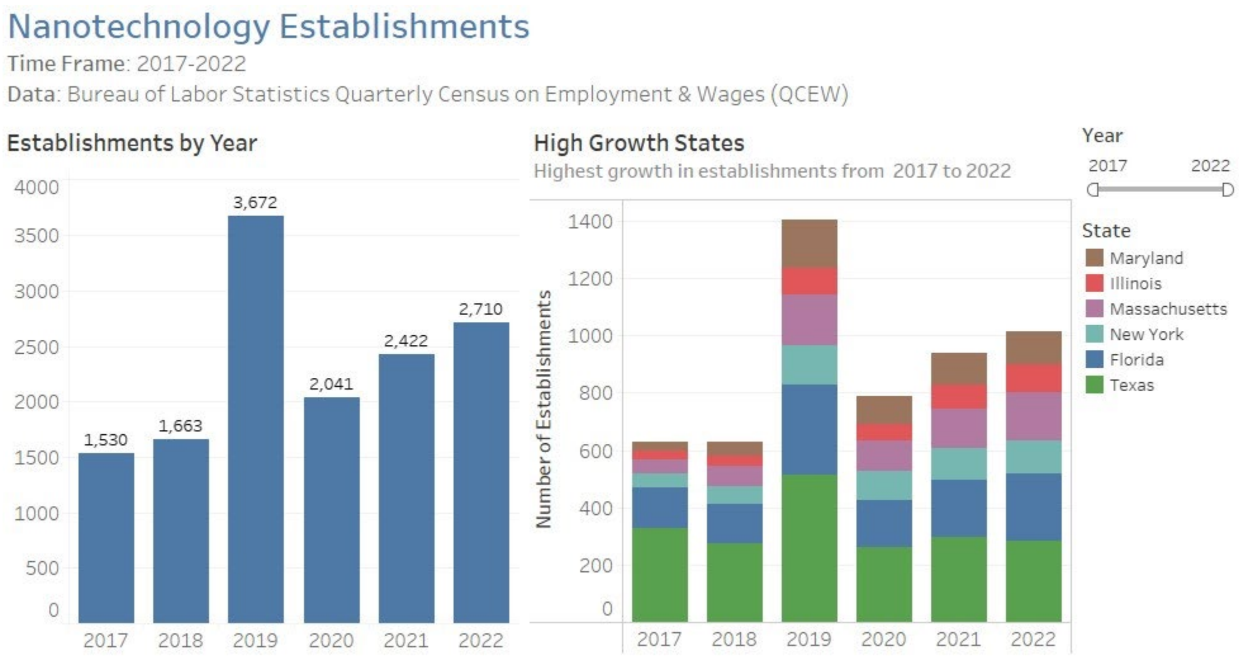

FIGURE 2: NANOTECHNOLOGY ESTABLISHMENTS

According to the Bureau of Labor Statistics (BLS), the number of establishments in the nanotechnology sector increased at a compounded annual growth rate (CAGR) of 11% between 2017 and 2022, with an increase observed from 2018 to 2019. Since the underlying source of the data is based on the NAICS code for 'Nanotechnology – Research and Development', it may exclude companies that do not identify nanotechnology research and development as their primary NAICS code. However, those establishments that do self-identify and use the NAICS code are more certain to be nanotechnology companies, meaning the BLS number of establishments, though conservative, is more confident and contains less noise in the data. Several states have seen significant growth in the number of establishments, as shown in Table 1.

TABLE 1: STATE GROWTH RATES

State	2017	2022	Growth (%)
Maryland	31	116	274%
Illinois	29	100	244%
Massachusetts	52	167	221%
New York	46	114	148%

MAP OF NANOTECHNOLOGY ESTABLISHMENTS IN THE CONTINENTAL U.S.[62], [63]

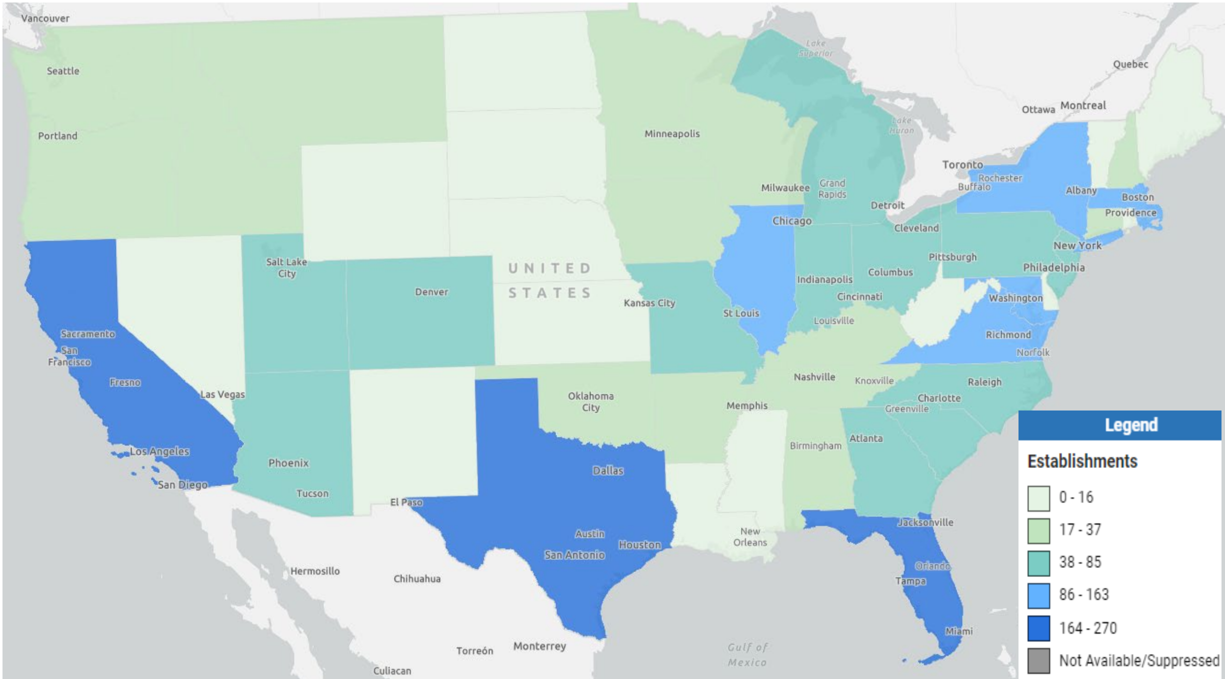

FIGURE 3: NANOTECHNOLOGY ESTABLISHMENTS - STATE VIEW

**Alaska and Hawaii report having 6 establishments each*

Total Economic Impact

To effectively determine the total dollar economic impact, number of jobs, and total dollar tax revenue for the period (2002-2022) of companies engaged in nanotechnology commerce, the team employed a multi-pronged approach to develop a series of estimates.

Estimate 1: Bureau of Labor Statistics (BLS) Analysis

Most nanotechnology firms are private companies and therefore have a limited mandate to make information related to economic impact available to the public. Two widely accepted data sources do look inside the workings of these firms: Bureau of Labor Statistics payroll figures, and the financial statements of public companies filed with the Securities & Exchange Commission (SEC).

In 2017, the Census Bureau established a NAICS industry code for the nanotechnology sector separate from other research & development industries (code 541713). This allowed BLS to release more detailed information on employers and their payrolls.

On the other hand, SEC filings for nanotechnology companies contain line items related to corporate revenue, R&D, and selling general & administrative (SG&A) expenses. Assuming that the majority of R&D and SG&A relate to a firm's payrolls and that the proportion of revenue devoted to payroll is similar across

[62] The map is based on American Community Survey data updated in in June, 2023 and data from the most recent Economic Census conducted in 2017.

[63]Census Business Builder. "Industry Map - Research and Development in Nanotechnology (541713)." https://cbb.census.gov/cbb/.

the industry, the BLS estimate of total wages combined with the R&D and SG&A data from SEC filings can be used to make a conservative estimate of total revenue in the private-sector industry.

The team used a sample of five publicly traded nanotechnology companies (a cross-section of firms chose to cover small-medium/large firms and all the product categories) and examined their SEC filings for the period ending December 31, 2022.[64] In these financial statements, all these firms explicitly described themselves as nanotechnology companies or primarily engaged in nano-related product lines. Table 2 shows selected line items and their average percentages of overall revenue in this sample of firms.

Table 2: Nanotechnology Companies – Operations

Line Item	Avg. % Revenue
Revenue	100%
Cost of Revenue	61%
Research & Development (R&D)	9%
Selling General & Administrative (SG&A)	17%
Source: Securities & Exchange Commission filings	

The average combined sum of R&D and SG&A expenses was 26% of topline revenue. Assuming 70% of this combined sum is devoted to payroll, and the rest to administrative expenses, the resultant ≈ 18% of revenue (25% x 70%) can be attributed to wages. This implies that an estimate for total corporate revenues in the nanotechnology space can be calculated by dividing the BLS wages figure by 17.6%, approximately 18%.

In the fourth quarter of 2022, the Quarterly Census of Employment & Wages (QCEW) reported $843 million in wages in the nanotechnology industry. Using the above technique, this implies total revenue in the space is $843 million $\div\ 18\% =$ $4.97 billion nationwide for the fourth quarter, and $20.8 billion for the calendar year.

Economic Impact: $20.8 billion in estimated total corporate revenue in calendar year 2022

To compute a 2017 figure, we can use the same method but substitute SEC financial statements from the period ending March 31, 2017. In that period, the average combined sum of R&D and SG&A expenses was 27% of topline revenue. Taking 70% of this gives us a divisor of 19%.

In the first quarter of 2017, the QCEW reported $782 million in wages in the industry and $2.766 billion for calendar year 2017. Dividing by 19%, this implies total revenue in the space was $4.115 billion nationwide for the quarter and $14.55 billion for the calendar year.

Prior Economic Impact: $14.6 billion in estimated total corporate revenue in calendar year 2017

[64] For our sample, we choose the following companies CVD Equipment ($CVV), Donaldson Co. ($DCI), Nanophase ($NANX), NVE Corporation ($NVE), VEECO Instruments ($VECO).

These estimates are the most conservative and establish the bottom bound of nanotechnology's economic impacts, Table 3 below summarizes the data.

TABLE 3: SUMMARY OF ESTIMATES (BLS)

Source	Year	NAICS Code	Number of Establishments	Workers	Corporate Revenues
Bureau of Labor Statistics (BLS)[65]	2022	541713	2, 660	27,890	$20.8 billion
Bureau of Labor Statistics (BLS)[66]	2017	541713	1,365	19,400	$14.55 billion

Estimate 2: Nanotechnology Company Analysis – Bottom-up Estimate

First, our team examined market size research. However, nanotechnology market size research varies considerably. As an example, Precedence Research[67] estimates the global nanotechnology market in 2022 at $97.42B. However, BCC Research[68] estimates the global nanotechnology market at $7.5B and the US market at $1.87B in 2022.

Using a curated list of nanotechnology companies, our team developed an estimated range of economic impact by examining the corporate revenues of public and private companies. As expected, it is challenging to develop such an estimate given the below specific constraints, in addition to the overall constraints identified in the earlier sections:

- Overall, private company revenues are not disclosed. So, it is challenging to estimate revenues for these companies.
- Most companies do not provide revenues by product lines – our effort was focused on using the baseline categories of Core Nano, Nano Tools, and some Integrated Nano.
- In addition, while public companies report revenues by geographic location, revenues are not reported by product line for each region.
- Many companies do not disclose that they use or develop nanotechnology-enabled products.

Using the process described earlier, our team conducted research to identify revenues for each company in the inventory. A summary is provided in Table 4 below.

TABLE 4: SUMMARY OF ESTIMATES (COMPANY ANALYSIS)

2022 Revenues ($)	2021 Revenues ($)	2002 – 2022 Revenues ($)
$67-83B	$53-65B	$928B - $1.1T

Given the constraints described earlier, the team developed a low and high-range estimate using a confidence range of 10%. Where available, the team identified revenues for 2022 and 2021 – in addition

[65]"Databases, tables & calculators by subject." U.S. Bureau of Labor Statistics. https://www.bls.gov/data/

[66] "Databases, tables & calculators by subject." U.S. Bureau of Labor Statistics. https://www.bls.gov/data/

[67] Precedence Research "Nanotechnology market size to surpass US$ 288.71 bn by 2030." Globe Newswire News Room. https://www.globenewswire.com/news-release/2022/04/15/2423346/0/en/Nanotechnology-Market-Size-to-Surpass-US-288-71-Bn-by-2030.html

[68]BCC Publishing. Global Nanotechnology Market, Global Nanotechnology Market Outlook & Growth Forecast Report. https://www.bccresearch.com/market-research/nanotechnology/global-nanotechnology-market.html

to determining revenues for the last 20 years based on a company's formation year. Data for prior years was often not available. As a result, the team had to rely primarily on data from public companies.

Industry Specific Case Study

As was previously established, the primary goal of this research project is to examine the economic impact that nanotechnology has had within the United States. To create a conservative and defensible minimum estimate, the research team aimed to limit the analysis to those firms directly and inarguably tied to nanotechnology.

The advantage of the approach is that it forms a strong and defensible baseline from which further conclusions, iterations, and follow-up research can be conducted. However, given our approach, the potential economic impact of nanotechnology is undercounted considering both Estimate 1 - Bureau of Labor Statistics (BLS) Analysis and Estimate 2 - Nanotechnology Company Analysis. This third estimate provides a sector perspective based on estimating the potential economic impact of a core sector (semiconductor and microelectronics sector) that is enabled by nanotechnology,

A Primer on Semiconductors and Micro-Electronic Devices

Semiconductors serve as the backbone of modern electronics, enabling the creation of transistors, diodes, and integrated circuits that power virtually all modern electronic devices. Previously, this report examined semiconductors as distinct from other electronic devices in the 'Key Product Groups and Industry Applications' section. The following primer provides additional context and rationale for why semiconductors were singled out this way.

Semiconductors are so widespread that they border on ubiquity in our daily lives and are an integral part of hundreds of finished products where nanotechnology may not otherwise be present. For example, semiconductors can be found in cell phones, tablets, computers, memory storage devices, 'smart' products, fitness devices, GPS-enabled devices, automobiles, planes, televisions, medical equipment, solar panels, digital and security cameras, home appliances, traffic lights, scientific instruments, industrial machines, agricultural equipment, LED lighting, remote controls, battery and energy components, and military equipment.

The key to the functionality of these devices lies in the use and manipulation of the electrical properties of semiconductor materials at the nanoscale. Nowadays, semiconductors and nanotechnology have an indistinguishably close relationship that arises from the fundamental principles governing semiconductor devices and the need for precise control and manipulation of materials and structures at the nanoscale to enable the performance of these devices.

The timeline of semiconductor development is a remarkable journey of continuous innovation and miniaturization, characterized by the increasing number of semiconductors per chip and the shrinking size of these devices. To better understand the deeply integrated nature of nanotechnology and modern-day semiconductors, a brief timeline of their technological advancement provided.

Semiconductor Development Timeline

The semiconductor industry began with the invention of the transistor, a fundamental electrical component that serves as a ‘switch’ or ‘amplifier’ for electronic signals, in 1947. In the 1950s and 1960s, the first integrated circuits (ICs) were developed. They contained a small number of transistors on a single chip with gaps of a few millimeters (mm, one-thousandth [1/1,000] of a meter) between them. In 1965, Gordon Moore made a now famous observation, known as Moore’s Law, which predicted that the number of transistors in a dense integrated circuit would double roughly every two years.[69]

The 1970s saw the introduction of the microprocessor, a specialized integrated circuit with a significantly larger number of transistors. Intel's 4004 microprocessor, released in 1971, had approximately 2,300 transistors. To increase the number of transistors, the size of the transistor, their relative ‘gate length’ (which determines how quickly the transistor can switch on and off), and the distance between transistors on a chip decreased into the microscale. The key size measurements were now just a few micrometer’s (µm, one-millionth [1/1,000,000] of a meter or one-thousandth [1/1,000] of a millimeter). This marked the beginning of the era of microelectronics, where chips started to perform complex tasks and technological transformation was enabled by computers.

1965 Gordon Moore makes his famous observation about component density in an article published in Electronics magazine.

1971 Intel introduces the first microprocessor, the 4004, helping usher in the consumer tech era.

1977 Apple introduces the Apple II personal computer, one of the first successful PCs, with the help of steadily more powerful microprocessors.

1989 Intel introduces the i860 processor, the first microprocessor with more than one million transistors, for use in supercomputing and scientific applications.

1993 Intel announces the creation of the Pentium processor, which contains nearly triple the number of transistors its predecessor had.

2005-07 Microprocessors’ clock speeds stop increasing as chips threaten to become as hot as the surface of the sun.

2007 As the number of transistors on a microchip exceeds one billion, Apple ships its first iPhones, transforming the phone into a handheld computer.

2015 Intel delays its shift to microprocessors based on the next-generation 10-nanometer manufacturing process, the biggest hint that Moore’s Law has broken down.

History of Semiconductors[70]

During the 1980s and 1990s, Moore's Law and the doubling rate of transistor counts held true, driving exponential growth in chip complexity and capabilities. By the late 1990s, microprocessors like Intel's Pentium II contained over a million transistors. Moore's Law continued to be the guiding principle throughout the 2000s, with chips crossing the billion-transistor mark and the key sizes for transistors continuing to shrink into the nanoscale (nm, one-billionth [1/1,000,000,000] of a meter or one-thousandth [1/1,000,000] of a millimeter. From this point on the colloquial term ‘microprocessor’ continued to be used to advertise and identify these products, even though the key sizes for processors were now well smaller than a micrometer.

In early 2004, semiconductors and microelectronics hit an inflection point. Historically, single-core Central Processing Units (CPUs) were the norm for microprocessors. These processors consisted of a single processing unit capable of executing instructions one at a time. As technology advanced, CPU capabilities,

[69] Markoff, John. “Moore’s Law Running out of Room, Tech Looks for a Successor.” The New York Times, May 4, 2016. https://www.nytimes.com/2016/05/05/technology/moores-law-running-out-of-room-tech-looks-for-a-successor.html.

referred to as ‘clock speeds’, increased to improve performance. However, as clock speeds rose, so did power consumption and heat.

In 2004, Intel “publicly acknowledged that it had hit a 'thermal wall' on its microprocessor line.”[70] “The industry saw signs that Moore’s Law was running out of steam as far back as 2005, when researchers began to worry that computer processors were becoming so hot that they would soon match the surface of the sun in heat output.”[71] More semiconductors and transistors could no longer be added to microprocessing chips to increase their performance because the chips were becoming too hot to function.

It was then that a breakthrough emerged - the development of multicore processors. The advent of the multicore processor helped address the thermal problem by allowing for increased performance to be achieved by dividing the tasks between multiple processors. Instead of relying solely on higher clock speeds, designs featured multiple processing cores on a single chip. Each core could manage tasks independently, allowing for parallel processing and improved overall performance.

However, even with the improved design of multi-core processors, heat and power consumption remained limiting factors, as the additional cores still generated some additional heat and required more power. Physical space also proved a challenge, as putting multiple processors on a chip necessitated more space, but increasing chip sizes also increased the distance between components and thus the speed at which they communicated by sending and receiving electrical signals. This underscored the need to continue to reduce the size of microprocessors as a means of managing the delicate balance of physical size limitations, heat generation, and energy use.

Advances in semiconductor fabrication technology and methods addressed these issues, in part, by reducing the size of the processor to the nanoscale. This reduced the power required, the heat generated, and the size required for multiple processors. Over a period of years in the 1990s and early 2000s, semiconductors and microelectronics became inherently integrated with nanotechnology. Various devices and components of chips were reduced to the nanometer scale (typically around 90nm to 45nm) to enable more processors and transistors to be packed onto a chip, while simultaneously reducing power consumption and space requirements. In fact, “by the mid-2000s, all high-tech competitors in the chip and semiconductor space were vying for the top spot by reducing the size of their transistors into the nanoscale.”[72]

Beginning in the early 2000s and into the present, semiconductors and advanced microelectronic devices use dozens of nanotechnologies, nanomaterials, nano-tools, and nanofabrication techniques. Modern semiconductors and microelectronic devices make use of lithography, atomic layer deposition, chemical

[70] Markoff, John. “Intel’s Big Shift after Hitting Technical Wall.” The New York Times, May 17, 2004. https://www.nytimes.com/2004/05/17/business/technology-intel-s-big-shift-after-hitting-technical-wall.html.

[71] Markoff, John. “Moore’s Law Running out of Room, Tech Looks for a Successor.” The New York Times, May 4, 2016. https://www.nytimes.com/2016/05/05/technology/moores-law-running-out-of-room-tech-looks-for-a-successor.html.

[72] EETimes. “IBM, Intel Wrangle at 90 Nm.” EE Times, December 13, 2002. https://www.eetimes.com/ibm-intel-wrangle-at-90-nm/.

vapor deposition, scanning tunneling microscopy, atomic force microscopy, and nanoscale etching. They can use various nanomaterials, like carbon nanotubes, graphene, nanowires, quantum dots, and more.

The use of nanotechnology enabled the continued evolution of chips and processors. The 2010s saw the proliferation of many specialty chips, designed to manage specific tasks more efficiently, like Graphics Processing Units (GPUs) and Tensor Processing Units (TPUs). The 2020s have seen the continued advancement of semiconductor technology using nanotechnology. The size of components has continued to shrink, many being 5 nm or smaller. Chips routinely have incredibly dense transistor counts, numbering in the hundreds of billions. (See Figure 3) [73] Looking to the future, innovative chip research has involved non-traditional semiconductor materials, like Silicon Carbide (SiC) or Gallium Nitride (GaN). Further, revolutionary size reductions are being researched in the realms of 'quantum computing'.

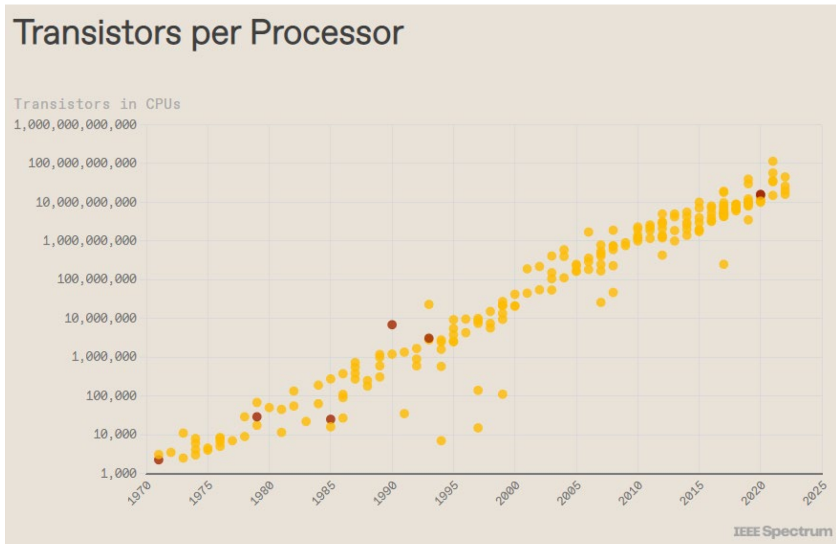

FIGURE 4: EVOLUTION OF TRANSISTORS

The history of semiconductor development is that of a relentless pursuit of more powerful processing capabilities through increasing both the number of transistors on a chip and simultaneously reducing the size of these devices. **Beginning in the mid-2000s, all chips that were competitive in the market became fundamentally dependent on nanotechnology, a condition that continues today.** Chips are constructed by manipulating materials at the nanoscale using nano tools and techniques for fabrication, characterization, and testing. It is in this way that the integrated and dependent nature of semiconductors and nanotechnology becomes self-evident.

Semiconductors and Microelectronics as an Indicator of Nanotechnology's Economic Impact

For the third estimate, the research team's goal was to provide additional context and perspective into the potential size of the economic impact of nanotechnology. This report identified 15 commercial areas of major impact for nanotechnology in the earlier section "Key Product Groups and Industry Applications." Each one of these areas can be seen as a partial contributor to the total economic impact of nanotechnology. Within each of these commercial areas, some of the economic impact is driven by nanotechnology and some is not. Throughout the research and analysis for this report, the team used a

[73] Darwish, Mahmoud. (2020). Memristive Behavior In Vanadium Dioxide Elements: Simulation And Modeling. https://www.researchgate.net/publication/334684192_Memristive_Behavior_In_Vanadium_Dioxide_Elements_Simulation_And_Modeling#pf2

foundational approach, emphasizing prudence and doubt, to formulate as cautious and dependable an estimate as possible.

Despite their clear dependency and integration with nanotechnology, semiconductor products were initially excluded from the company estimate because (1) the exact time when semiconductors became inherently integrated with nanotechnology is not precise and the range of time assessed includes some years when that transition was still taking place and (2) the data available for companies operating in the space lacked the specificity required to make a conservative and reliable estimate. Most firms operating in this sector report aggregated revenue, including lines of business that are not related to semiconductors, and therefore not a part of nanotechnology's economic impact. Including them would have introduced more variability into the estimate, and thus semiconductors were not included in the initial company estimate.

The previous historical timeline examined the evolution of semiconductors over the past 8 decades, concluding that modern semiconductors and microelectronic devices rely so heavily upon nanotechnology as to be fundamentally dependent. This section builds on the analysis in Estimate 1 and Estimate 2 by creating an additional estimate of the semiconductor sector as an alternative estimate for nanotechnology's impact on a sector. This sector was selected because among the 15 commercial areas examined, the semiconductor sector stands out as the one most clearly connected with nanotechnology, particularly in the present day.

An additional reason for the focus on semiconductors is that they represent one of the clearest examples of how nanotechnology is used to drive the American economy. Semiconductors and microelectronics are increasingly a focus of American politics, as is evidenced by the fact that the CHIPS and Science Act "passed Congress with substantial bipartisan support in both the Senate and the House. [And] dedicates $52 billion in federal funds to support new semiconductor plants, high-tech education, product development, and domestic manufacturing."[74]

Due to the widespread uptake throughout dozens of industries, semiconductors form an incredibly important aspect of the U.S. Economy. A recent Statista report indicated that "in 2022, semiconductor sales reached 580.13 billion U.S. dollars worldwide."[75] American firm's market share of the global revenue is disputed, with some estimates placing the U.S. third globally with nearly ~25%[76] of the market share while industry advocates recently claimed "U.S.-based firms [had] the largest market share with 47 percent."[77]

[74] Seeberger, Colin., Gibbs Leger, Daniella., and Ragland, Will. "What's the Point? Americans Support the Chips and Science Act." Center for American Progress Action, August 9, 2023. https://www.americanprogressaction.org/article/whats-the-point-americans-support-the-chips-and-science-act/.

[75] Alsop, Thomas. "Global Semiconductor Market Size 2023." Statista, May 4, 2023. https://www.statista.com/statistics/266973/global-semiconductor-sales-since-1988/.

[76] Alsop, Thomas. "Semiconductor Market Size by Region 2022." Statista, March 1, 2023. https://www.statista.com/statistics/249509/forecast-of-semiconductor-revenue-in-the-americas-since-2006/.

[77] Semiconductor Industry Association. "Chipping In The Positive Impact of The Semiconductor Industry on The American Workforce and How Federal Industry Incentives Will Increase Domestic Jobs." https://www.semiconductors.org/wp-content/uploads/2021/05/SIA-Impact_May2021-FINAL-May-19-2021_2.pdf.

Estimate 3: Semiconductor and Microelectronics Sector Analysis

Methodology

The research team applied a methodology like the company analysis conducted for Estimate 2. A list of products, tools, and techniques (Table 5) was developed to help identify firms that were involved in semiconductor manufacturing, refinement, and testing. Each firm's product list, as well as other key descriptors like their mission statements or 'about' sections, were cross-referenced using the list to identify if and to what extent the firm was involved in the semiconductor and microelectronic sector.

TABLE 5: SEMICONDUCTOR AND MICROELECTRONIC DEVICES AND FABRICATION TECHNIQUES LIST

Component	Fabrication Tool/Technique
Transistors	Photolithography
Logic Gates	Electron Beam Lithography (e-beam litho)
Flip-Flops	Extreme Ultraviolet (EUV) Lithography
Multiplexers and Demultiplexers	Atomic Layer Deposition (ALD)
Adders and Arithmetic Logic Units (ALUs)	Chemical Vapor Deposition (CVD)
Registers	Reactive Ion Etching (RIE)
Cache Memory	Deep Reactive Ion Etching (DRIE)
Control Units	Scanning Tunneling Microscopy (STM)
Clock Generators	Atomic Force Microscopy (AFM)
Clock Distribution Network	Vapor-Liquid-Solid (VLS) Growth
Bus Interface Units	Chemical Vapor Deposition (CVD)
Memory Cells	Quantum Dot Synthesis
Input/Output (I/O) Ports	Silicon on Insulator (SOI) Fabrication
Floating-Point Units (FPUs)	Self-Assembly Techniques
Graphics Processing Units (GPUs)	Scanning Electron Microscopy (SEM)
Vector Processors	Transmission Electron Microscopy (TEM)
Memory Controllers	X-ray Diffraction (XRD)
Digital Signal Processors (DSPs)	X-ray Photoelectron Spectroscopy (XPS)
Phase-Locked Loops (PLLs)	Secondary Ion Mass Spectrometry (SIMS)
Power Management Units (PMUs)	Electron Spectroscopy for Chemical Analysis (ESCA)
Security Modules	X-ray Fluorescence (XRF)
On-Chip Sensors	Nuclear Magnetic Resonance (NMR)

Component	Fabrication Tool/Technique
Interconnects and Routing	Time-of-Flight Secondary Ion Mass Spectrometry (TOF-SIMS)

Additionally, the research team analyzed industry databases of semiconductor foundries and production facilities and the companies that owned and operated them to populate the preliminary list. The initial list consisted of 56 firms identified across the United States. This list was further refined, leaving 34 firms for inclusion in the economic analysis. Firms were excluded from analysis using the following criteria, recognizing once again that some distinctions required subjective interpretation.

TABLE 6: SEMICONDUCTOR AND MICROELECTRONIC DEVICES CRITERIA

Criteria	Description
Company	• Is the company headquartered in the U.S.? • Are more than 50% of the company's production and/or fabrication facilities located in the U.S.?
Product	• Do products align with one or more of the semiconductor and microelectronic devices identified? • Does semiconductor and microelectronic devices manufacturing, production, refinement, or testing represent the core business?

The resultant list contained several household names, like Intel and Micron. But a few other large firms were excluded from this analysis. For example, IBM and Motorola were excluded because, though they were once deeply involved in the sector, each group had sold off or spun off their semiconductor and chips manufacturing businesses by 2022. Apple and Samsung, two companies that are dominant players in the industry, were excluded as both conduct the majority of their production and fabrication of semiconductor and microelectronic components outside of the U.S. and either import finished products or semi-finished products that are ready for final assembly.

Assumptions and Constraints

Discrete data on the production and use of semiconductors is limited by the following constraints:

- Many firms both produce and integrate semiconductors into their own finished products, limiting the information available about the revenue semiconductor fabrication produces as those revenues are ultimately realized with the final sale of the finished product.
- Many companies do not parse out segment data for semiconductor production in their financial reporting in order to maintain trade advantages over their competitors and private knowledge about their techniques, production, and costs.
- U.S. regionally exclusive revenues are similarly not available for some of the firms involved in the manufacturing of semiconductors and microelectronics as many are multinational companies and report their total revenue.

As a result, the research team used total company revenue for this analysis, which has several advantages and disadvantages. An advantage is that many companies in the semiconductor space are quite large and are publicly traded, meaning the available revenue data is reliable, as it is audited and reported to several financial institutions including the SEC. A disadvantage is that many of the companies analyzed have elements of their business, like consulting practices, data analytics and hosting services, software services, commercial business products like printer ink, and more, that fall outside of the scope of semiconductor production and therefore are not a part of the broader nanotechnology economy.

Additionally, though many of the firms analyzed operate exclusively in the U.S., some are multinational corporations and it is unclear what portion of their revenue can be solely attributed to the U.S. Accordingly, there is some specificity and reliability concerns with the data, but, as this is formative and preliminary research, this industry analysis treats revenue totals as a proxy to inform the potential economic impact of one sector that is intrinsically tied to nanotechnology.

After conducting the analysis, the research team estimated that the semiconductor and microelectronics sector yielded a range of $268-297 B in corporate revenues in calendar year 2022.

Economic Impact: $268-297 billion in estimated semiconductor sector revenue in calendar year 2022

Interpreting the Three Nanotechnology Estimates

FIGURE 5: VISUALIZING NANOTECHNOLOGY'S IMPACT

These estimates, when taken together, are analogous to an iceberg. The most readily accessible information is the top of the iceberg—the values tracked by the Bureau of Labor Statistics. However, delving deeper into the analysis uncovers submerged layers of intricacy and nuance. Many companies do not identify using the BLS's primary data source – the Nanotechnology R&D NAICS code – but are still involved in the broader nano-economy. These concealed details are analogous to the submerged bulk of the iceberg beneath the waterline, not immediately apparent but vital in understanding the true extent of the economic impact of nanotechnology. Just as the iceberg's true total mass remains hidden, additional information derived from Estimate 2 and Estimate 3, the Company Inventory analysis and Semiconductor Sector analysis, both offer deeper perspective into nanotechnology's total economic impact. That being said, there are additional nanotechnology products outside of the primary categories of Core Nano and Nano Tools used in the Company Inventory estimate, just as there are industries where nanotechnology is being integrated beyond the semiconductor sector. This analogy underscores the importance of context in understanding the layers of potential activity driven by nanotechnology throughout the economy, as well as the potential size range of nanotechnology's true total impact.

TABLE 7: COMPARISON OF ESTIMATES

Estimate 1: Bureau of Labor Statistics	Estimate 2: Company Inventory	Estimate 3: Semiconductor Sector
$20.8 B	$67-83 B	$268-297 B

There are opportunities to refine and build upon this initial analysis. Similar analysis could be conducted for some of the other fifteen industries and areas mentioned in the industry analysis section, like healthcare, pharmaceutical production, oil and gas refinement, or cosmetic products. Follow-up analysis could develop more specific measurements of the semiconductor business segments of larger companies and American revenues of multinational corporations, as those were limiting factors of this estimate due to both timing and data availability constraints. With that said, using the semiconductor and microelectronics industry to provide additional context and perspective for the total economic impact of nanotechnology can be a reasonable approach to better understand nanotechnology's economic impact on a key sector.

These devices have evolved over the last two decades to be so dependent and integrated that modern semiconductors cannot exist without nanotechnology. In this way, they are a product that is primarily attributable to nanotechnology and thus can be counted as part of the economic impact of nanotechnology.

The pace at which the semiconductor industry is growing is tremendous, with "the semiconductor market size [globally] projected to grow from USD 573.44 billion in 2022 to USD 1,380.79 billion in 2029 at a Compound Annual Growth Rate (CAGR) of 12.2%."[78] Semiconductors and advanced electronic devices are just one of the truly exceptional success stories from the world of nanotechnology and are poised to be one of the most important economic focuses in the world. The role that nanotechnology has played in this success story has been nothing short of fundamental, and the future is bright for innovators in the industry.

Economic Impact by State

Not all establishments and employees can be clearly associated with a single state. At the firm level, some firms may not disaggregate their operations over multiple locations when they make their reports. At the location level, some firms are the only ones in their industry operating in a given location. Reporting this data would unduly reveal the business operations of private citizens, so the BLS masks disclosure in these geographies. As a result, national aggregate figures may not always equal the sum of all state figures.

The below table provides a summary of the economic impact by state for 2022, including both the number of employees and payroll data.

[78] Fortune Business Insights. "Semiconductor Market Size Predicted to Reach USD 1,380.79 Billion, Exhibiting a 12.2% CAGR by 2029." GlobeNewswire News Room, April 5, 2023. https://www.globenewswire.com/news-release/2023/04/05/2641501/0/en/Semiconductor-Market-Size-Predicted-to-Reach-USD-1-380-79-Billion-exhibiting-a-12-2-CAGR-by-2029.html.

Table 8: Economic Impact by State (Source: Bureau of Labor Statistics)

State	Employees (2022)	Payrolls (Annual 2022)
Alaska	53	$469,898
Arizona	743	$80,809,718
Arkansas	88	$12,832,374
California	4,706	$744,739,827
Colorado	177	$32,397,580
Connecticut	40	$8,961,908
Delaware	39	$737,358
District of Columbia	36	$5,651,763
Florida	1,046	$146,856,165
Georgia	263	$33,659,313
Hawaii	7	$989,287
Idaho	25	$2,444,492
Illinois	887	$164,090,480
Indiana	268	$35,076,462
Iowa	91	$13,515,749
Kansas	7	$449,481
Kentucky	225	$32,378,648
Louisiana	81	$6,426,907
Maryland	1,300	$152,570,087
Massachusetts	2,025	$281,831,042
Michigan	115	$18,733,795
Minnesota	1,297	$182,666,624
Mississippi	7	$176,842
Missouri	848	$126,327,852
Montana	339	$32,224,764
Nebraska	161	$15,352,621
Nevada	55	$20,974,813
New Hampshire	45	$7,035,757
New Jersey	768	$98,483,210
New Mexico	57	$4,138,518
New York	963	$92,100,229
North Carolina	343	$47,727,413
Ohio	206	$25,537,853
Oklahoma	228	$19,996,552
Oregon	164	$19,119,446
Pennsylvania	1,159	$200,935,870
Rhode Island	7	$561,915
South Carolina	423	$53,107,097

State	Employees (2022)	Payrolls (Annual 2022)
South Dakota	25	$605,555
Tennessee	225	$30,812,709
Texas	1,287	$206,918,495
Utah	2,331	$191,112,695
Vermont	3	$350,973
Virginia	640	$70,181,488
Washington	774	$121,602,195
West Virginia	12	$1,319,731
Wyoming	21	$2,672,428
Other	3,407	$399,860,027
Totals		**$3,747,056,108**

Employment Overview

In January 2002, the Bureau of Labor Statistics (BLS) found that nearly 18,000 Americans worked in the nanotechnology industry on a seasonally adjusted basis. That number rose to 29,000 in May 2023, a 61% increase.

Nanotechnology employment gained steadily through the Global Financial Crisis before reaching a cyclical peak of 23,800 in March 2016. The cycle bottomed out at 18,900 jobs in March 2019 before returning to its upward trend. Job loss during the pandemic in this sector was modest, with a decline of only nine hundred nationwide between January-April 2020. The sector regained this job loss by December 2020 and has continued to gain in the years since.

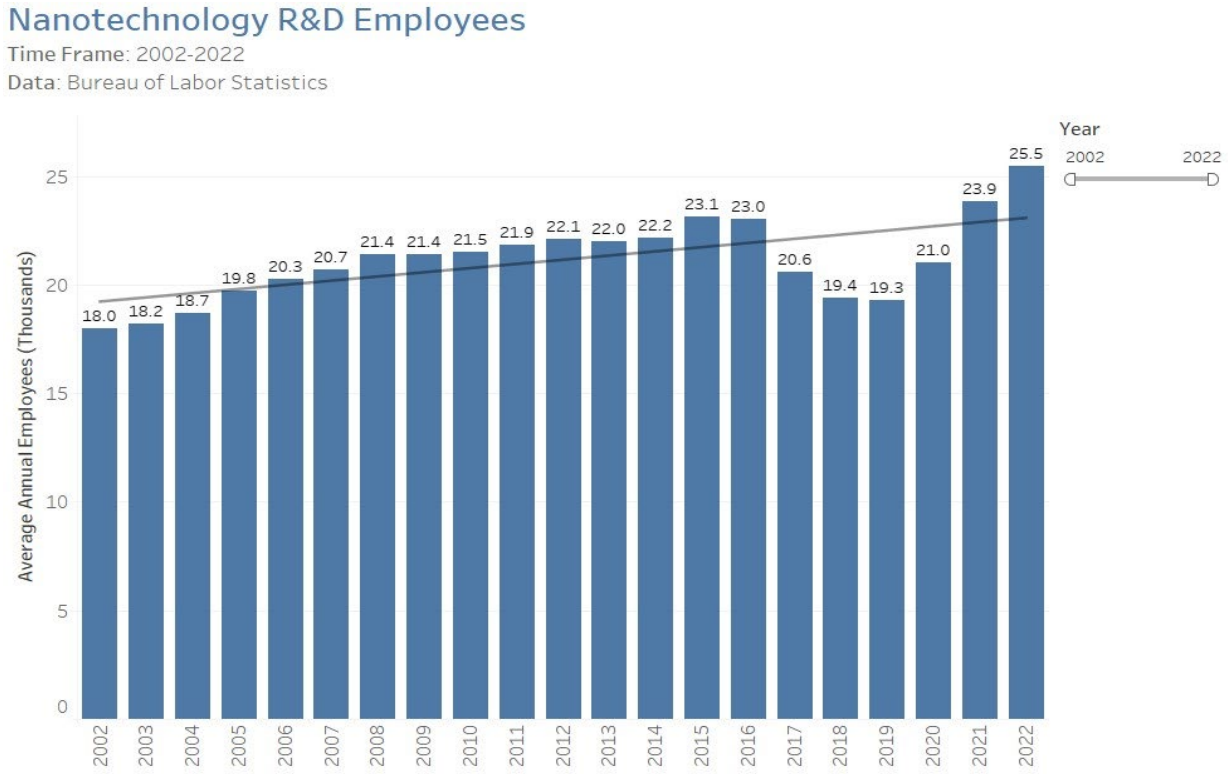

FIGURE 6: NANOTECHNOLOGY R&D EMPLOYEES

Over the period from 2002 – 2022, there is a steady 14-year trend of increased employment in the nanotechnology R&D industry section from 2002 to 2016. A deviation of this trend occurs from 2017 to 2020 but it returns to the previous 14-year trend post-COVID in 2021 and 2022. A recent Congressional Research Service (CRS) report highlights potential workforce shortages in new and emerging science and engineering fields, such as nanotechnology.[79]

In the first quarter of 2017, the BLS' QCEW found 1,360 private & public establishments in the nanotechnology R&D NAICS code employing 24,300 people.[80] These employees received $782 million in wages during that quarter, an average weekly wage of $2,470 or over $128,000 annually.

In the fourth quarter of 2022, the QCEW reported 2,660 establishments, a 96% increase in private & public employers in seven years. These firms employed 27,800 people (an increase of 15% in seven years) and paid wages of $896 million, or $2,470 per week (flat over seven years). The total amount of wages paid in 2022 was $3.74 billion.

Economic Impact: $3.74 billion in wages in calendar year 2022

[79] Johnson, Dexter. "Nanotech Employment Numbers Remain Inscrutable." IEEE Spectrum, June 24, 2021. https://spectrum.ieee.org/nanotech-employment-numbers-remain-inscrutable-.

[80] The seasonally adjusted monthly data series found 21,400 employees during the same quarter. The differences between the two figures come from the nature of the different surveys that collect this data and should be not seen as contradictory.

There are several states with significant increases in total wages within the nanotechnology workforce from 2017 to 2022, as summarized in the below table.

Table 9 – High Wage States

State	2017 Wages	2022 Wages	Growth (%)
Tennessee	$2.6M	$30.8M	1,087%
Georgia	$3.1M	$33.7M	986%
New Jersey	$9.4M	$94.5M	941%
Colorado	$3.25M	$32.4M	894%
New York	$12.9M	$92.1M	612%

Some of the incredible growth observed in these states is attributable to regional coordination and investment initiatives. Innovation hubs, technology corridors, and other R&D ecosystems regionally drive technology- and innovation-centric growth, serving as catalysts for job creation and broader economic growth. States such as Georgia and New York established nanotechnology-specific clusters to advance research and enhance the interactions between institutions and markets.

The Southeastern Nanotechnology Infrastructure Corridor (SENIC) was established in 2015 through the NSF-funded National Nanotechnology Coordinated Infrastructure to provide researchers in Georgia access to facilities and instruments that advance all disciplines of nanoscale science. SENIC supports 40-50 companies each year from single processes or measurements to multi-year ongoing engagements, demonstrating the corridor's ability to bring thought leaders from across the region together to advance discoveries and build businesses[81].

New York launched the NY Loves Nanotech campaign, a region-wide effort to invest in nanotechnology throughout Rochester, Syracuse, Utica, and Albany. NY Loves Nanotech brings together economic developers, 130 research institutions, and private sector partners to accelerate New York State's high-tech corridor, which claims to host over 400,000 jobs in New York State[82]. The investments made in both Georgia and New York created ecosystems that drive R&D and contribute economic growth.

Nanotechnology – Wages and Income

Total wages have been constant on an aggregate level with a significant spike in 2019, correlated with the increase in nanotechnology firms, also observed in 2019. Total wages have returned to their trends and are showing steady annual increases of 10% YoY from 2020, which is consistent with the growth seen in new firms joining the sector.

[81] SENIC. "Success Stories and Testimonials." https://senic.gatech.edu/success-stories-and-testimonials/

[82] NY Loves Nanotech. "About New York Loves Nanotech." https://www.nylovesnano.com/about.html

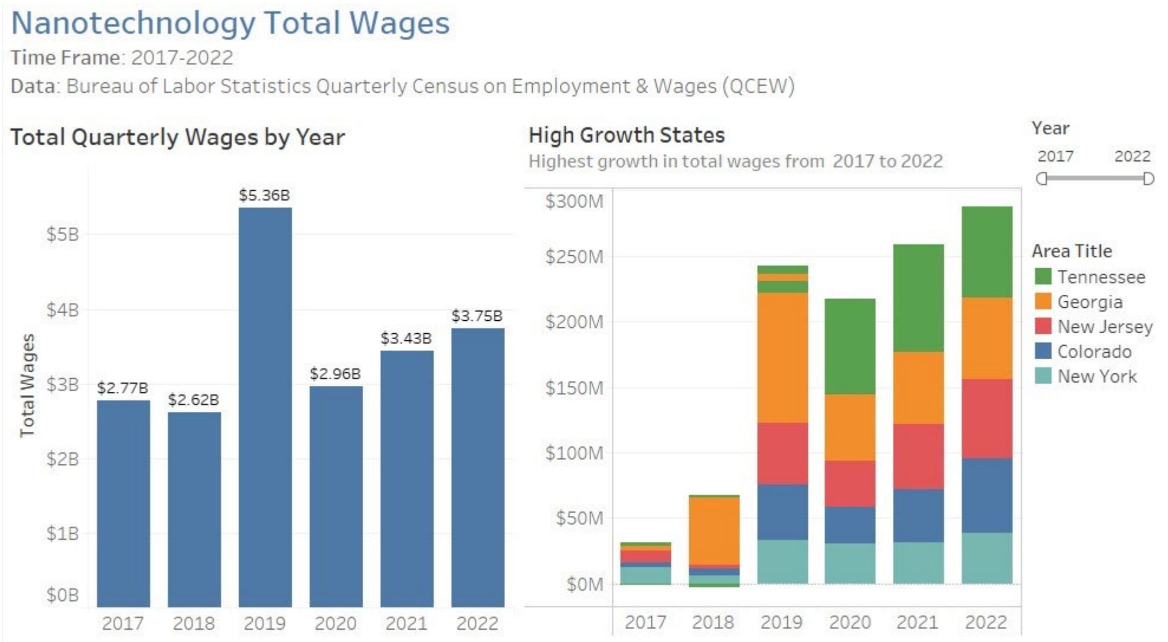

FIGURE 7: NANOTECHNOLOGY TOTAL WAGES

In the fourth quarter of 2022, the QCEW reported 2,660 establishments. These firms employed 27,800 employees and paid wages of $896 million, or $2,470 per week (flat over seven years) which amounts to an average salary of **$128,440** in 2022. To expand upon this estimate, the research team looked at professional, career, and recruiting resources online to develop a better understanding of the range of salaries for those working in the nanotechnology industry.

TABLE 10 – NANOTECHNOLOGY SALARY AVERAGES

Source	Role	Annual Salary (Average)
U.S. Department of Labor – O*Net Online[83]	Nanotechnology Engineering Technologists and Technicians	$61,210
PayScale[84]	Nanotechnology Research and Development	$79,000
Comparably[85]	Nanotechnology Engineer	$82,395
ZipRecruiter[86]	Nanotechnology Engineer	$95,023

[83] O*NET OnLine. National Center for O*NET Development. 17-3026.01 - Nanotechnology Engineering Technologists and Technicians. https://www.onetonline.org/link/summary/17-3026.01
[84] PayScale. "Salary for Industry: Nanotechnology Research and Development." https://www.payscale.com/research/US/Industry=Nanotechnology_Research_and_Development/Salary.
[85] Comparably. "Nanotechnology engineering salary - August 2023." https://www.comparably.com/salaries/salaries-for-nanotechnology-engineering.
[86] ZipRecruiter. "$80k-$129K nanotechnology engineer jobs." https://www.ziprecruiter.com/Jobs/Nanotechnology-Engineer.

CareerExplorer[87]	Nanotechnology Engineer	$100,640
Glassdoor[88]	Nanotechnology Engineer	$101,799
U.S. Department of Labor – O*Net Online[89]	Nanosystems Engineer	$104,600
Bureau of Labor Statistics Quarterly Census on Employment and Wages	Nanotechnology Employee	$128,440
Range: $61,210 - $128,440		

By comparison, the 2021 median household income in the U.S. was $69,717. The per-capita income was $38,332, placing nanotechnology jobs well above the national averages. To provide a more contextually comparable analysis, the research team looked at a selection of professions in comparable high-tech or high-education industries. The team identified careers in the U.S. Bureau of Labor's Experience Requirement 'Zone Four', those that require 'considerable preparation, training, and credentials.'

Table 11 – Comparable Jobs and Salaries

Job Title	Annual Salary (Average)
Histotechnologists[90]	$57,380
Chemists[91]	$80,670
Bioengineers and Biomedical Engineers[92]	$99,550
Materials Scientist[93]	$104,380
Microsystems Engineer[94]	$104,600
Photonics Engineers[95]	$104,600
Biofuels/Biodiesel Technology and Product Development Managers[96]	$159,920

[87] CareerExplorer. "Nanotechnology Engineer Salary." - CareerExplorer, November 14, 2019. https://www.careerexplorer.com/careers/nanotechnology-engineer/salary/.
[88] Glassdoor. "Salary: Nanotechnology engineer in United States August 2023 - Glassdoor." https://www.glassdoor.com/Salaries/nanotechnology-engineer-salary-SRCH_KO0,23.htm.
[89] O*NET OnLine. "National Center for O*NET Development. 17-2199.09 – Nanosystems Engineers." https://www.onetonline.org/link/summary/17-2199.09
[90] O*NET OnLine. "National Center for O*NET Development. 29-2011.04 - Histotechnologists." https://www.onetonline.org/link/summary/29-2011.04
[91] O*NET OnLine. "National Center for O*NET Development. 19-2031.00 - Chemists." https://www.onetonline.org/link/summary/19-2031.00
[92] O*NET OnLine. "National Center for O*NET Development. 17-2031.00 - Bioengineers and Biomedical Engineers." https://www.onetonline.org/link/summary/17-2031.00
[93] O*NET OnLine. "National Center for O*NET Development. 19-2032.00 - Materials Scientists." https://www.onetonline.org/link/summary/19-2032.00
[94] O*NET OnLine. "National Center for O*NET Development. 17-2199.06 - Microsystems Engineers." https://www.onetonline.org/link/summary/17-2199.06
[95] O*NET OnLine. "National Center for O*NET Development. 17-2199.07 - Photonics Engineers." https://www.onetonline.org/link/summary/17-2199.07
[96] O*NET OnLine. "National Center for O*NET Development. 11-9041.01 - Biofuels/Biodiesel Technology and Product Development Managers." https://www.onetonline.org/link/summary/11-9041.01

Range: $57,380 - $159,920

Nanotechnology Employment Demographics

According to CareerExplorer,[97] 26% of nanotechnology engineers are female and 74% are male in 2023. Data from 2019 showed that more males than females were interested in becoming nanotechnology engineers at a ratio of 3.45 to 1. The largest ethnic group of nanotechnology engineers are South Asian, making up 30% of the population. The next highest segments are White and Hispanic, Latino, or Spanish, making up 28% and 14% respectively.

Throughout the economic research and development of the company inventory, the team was able to find data on employment demographics for only a small handful of companies since very few companies currently track or report it publicly. The information that was available was, unfortunately, from too small a sample to draw any reasonable conclusions about the demographics across the nano workforce.

Further, The Census' Business Builder Tool (CBB), which allows for investigation and visualization of business data tracked by the Census, reported that workforce characteristic data was "not available for selected industry" when searching using the nanotechnology NAICS code.[98]

While there is limited data available on employment demographics, a recent Pew report on the science, technology, engineering, and math (STEM) workforce[99] found that Black and Hispanic workers remain underrepresented in the STEM workforce compared with their share of all workers. The representation of women varies widely across STEM occupations, but they remain underrepresented in other job clusters, such as the physical sciences, computing, and engineering.

[97]CareerExplorer. "Nanotechnology Engineer Demographics in the United States." CareerExplorer, November 14, 2019. https://www.careerexplorer.com/careers/nanotechnology-engineer/demographics/#:~:text=The%20largest%20ethnic%20group%20of,28%25%20and%2014%25%20respectively.

[98] Census Business Builder. "Census Business Builder - Research and Development in Nanotechnology." https://cbb.census.gov/cbb/#view=map&industries=541713&clusterName=Research+and+development+in+nanotechnology.

[99] Nadeem, Reem. "Stem Jobs See Uneven Progress in Increasing Gender, Racial and Ethnic Diversity." Pew Research Center Science & Society, April 1, 2021. https://www.pewresearch.org/science/2021/04/01/stem-jobs-see-uneven-progress-in-increasing-gender-racial-and-ethnic-diversity/.

Conclusion and Opportunities

Nanotechnology has revolutionized science, industries, labor groups, regional economies and more across the U.S. and is increasingly present at all levels of the national economy, from manufacturing to consumer products. However, the lack of clear consensus on the definition of what is a core nanotechnology product complicates quantifying the economic impact of nanotechnology companies and products. Given the constraints and data limitations, the estimate of **$20.8 billion (2022 revenues)** derived from the Bureau of Labor Statistics (BLS) data is a conservative estimate of the impact of nanotechnology but is an undercount of the total economic impact, as it only includes companies that are primarily in nanotechnology R&D. Building on this baseline estimate, using a combination of product and company analysis, provides an estimate of **$67-83 billion** (2022 revenues), much higher than the BLS estimate but still a moderate estimate given the research team's focus on limiting the analysis to primary nanotechnology products. Examining the Semiconductor and Microelectronics sector provides an alternative approach and results in an estimate of **$268-297 billion** (2022 revenues), again higher than the company analysis but still not the full scope of the nano-economy.

Given the revolutionary impact of nanotechnology and the proliferation and uptake it has seen in non-R&D settings, the BLS should consider adding additional NAICS codes to the nanotechnology sector to better track and collect data on the sector. As there are currently many establishments using nanotechnology in their products or manufacturing that would not identify themselves primarily as a nanotechnology R&D company, the existing NAICS code may insufficiently capture the full nano-economy.

While the primary purpose of the study was to determine the economic impact of nanotechnology, there are several other significant benefits from this work. First, the set of product categories identified through the product repository serves as a starting point and opportunity for the NNI to curate, refine, and further track the impact of nanotechnology's continued and burgeoning impact across various industries and sectors. Subsequently, the economic impact assessment and broader growth trends can be made more precise by continuing to identify additional products and establishments in the nano-economy, filling gaps as the products and categories become more robust and articulated and new firms enter the space.

Second, there is a valuable opportunity for the NNI to continue to engage with industry to obtain economic impact data, along with examples of innovative products and applications in the industry. In turn, there is an opportunity for an industry led entity to establish strategic initiatives to engage members, conduct an annual survey of firms, provide a forum to share innovative applications and products, enhance coordination and collaboration within the supply chain, develop a nanotechnology company database, and other priorities. Such a nanotechnology ecosystem can further enhance collaboration and coordination in the industry and allow its members to obtain key industry insights and trends.

Finally, and most importantly, the baseline estimates provided in this report, are a starting point and are limited due to project schedule and data availability constraints – as a result, there needs to be a sustained, longer-term effort to refine and curate the list of products, companies, sectors, and the economic impact of nanotechnology.

Appendix A – Nanotechnology Product Categorization Repository

Product Name	Category	Product Description
Aluminium oxide nanoparticles/Nano-alumina	Core Nano	A nanomaterial that exhibits low electric conductivity, resistance to chemical attack, high strength, extreme hardness, and high melting point.
Antimony tin oxide nanoparticles/nanopowders	Core Nano	Antimony tin oxide nanoparticles/nanopowders (nano-Sb) possess excellent optical properties, chemical and mechanical stabilities, and high conductivity. They are mainly used in electronics and optics applications, where they are utilized for their high electrical conductivity and optical transparency.
Bismuth oxide nanoparticles	Core Nano	Bismuth oxide properties include thermal and electrical transport, large surface area, high refractive index, large energy gap, dielectric permittivity, exceptional photoluminescence and photoconductivity, and good electrochemical stability.
Carbon nanotubes	Core Nano	A carbon nanotube (CNT) is a tube made of carbon with a diameter in the nanometer range (nanoscale). They are one of the allotropes of carbon. Used in an attempt to offer higher durability for treated fabrics as they hold high surface energy and large surface area that ensures improved affinity for fabrics and increase the durability of textile functions. Carbon nanotubes can be single walled or multi walled, with the number of walls impacting the qualities and applications of the nanotube.
Cerium oxide nanoparticles	Core Nano	Cerium oxide (ceria) nanoparticles (Nanoceria/CeO2-NPs) are properties include ability to act as a catalyst for both oxidation and reduction reactions, high ionic conductivity, and UV-filtering. Current and potential uses exist in catalytic, energy, environment protection and biomedical applications.
Cobalt oxide nanoparticles	Core Nano	Cobalt oxide nanoparticles have a wide range of exceptional structural, electrical, magnetics and catalytic properties including:
Copper oxide nanoparticles	Core Nano	Copper oxide nanoparticles are utilized in semiconductor devices, gas sensor, batteries, solar energy converter, microelectronics and heat transfer fluids.

Product Name	Category	Product Description
Dendrimers	Core Nano	Dendrimers are synthetically produced monodisperse polymeric nanostructures originating from a central core molecule and surrounded by successive addition of branching layers. These structures exhibit a high degree of molecular uniformity, narrow molecular weight distribution, tunable size and shape characteristics, as well as multivalency
Fullerenes	Core Nano	A fullerene is an allotrope of carbon whose molecule consists of carbon atoms connected by single and double bonds so as to form a closed or partially closed mesh, with fused rings of five to seven atoms. Typically used for their heat resistance and superconductivity properties.
Gold nanoparticles	Core Nano	Gold nanoparticles are widely used due to unique optical properties, such as strong light scattering, intense absorption, and electromagnetic field enhancement.
Graphene	Core Nano	Graphene is a nanomaterial (single layer of carbon atoms, tightly bound in a hexagonal honeycomb lattice) used for its toughness, flexibility, and resistance in the construction, health, and electronics sectors.
Iron oxide nanoparticles	Core Nano	Iron oxide nanoparticles have attracted extensive interest due to their super paramagnetic properties including an ability to interact with various biological molecules in different ways due to their superparamagnetic properties, high specific area and wide choice of surface functionalization.
Lipid nanoparticles	Core Nano	A type of nanotechnology-based drug delivery system that consists of lipids, which are fats or fat-like substances, designed to encapsulate and deliver therapeutic compounds, such as drugs or nucleic acids (RNA or DNA), to specific target sites in the body.
Liposomes	Core Nano	Nanoscale vesicles composed of lipid bilayers, which are similar in structure to the cell membranes found in living organisms. Liposomes are one of the most widely studied and used nanocarriers in drug delivery and nanomedicine.
Magnesium oxide nanoparticles	Core Nano	Magnesium oxide nanoparticles have exceptional chemical, thermal, electrical and optical properties including high thermal stability and melting point, high surface reactivity, mechanical stability, and small dielectric constant.
Manganese oxide nanoparticles	Core Nano	Manganese oxide nanoparticles poses superior optical, magnetic, electrical and chemical properties. They also display lower toxicity than other nanomaterials show potential for application in superconductors, catalysts, sensors, battery, corrosion resistant and high temperature applications.

Product Name	Category	Product Description
Metal-organic frameworks (MOFs)	Core Nano	Porous materials composed of metal ions or clusters coordinated with organic ligands. MOFs have a highly ordered and crystalline structure, with a network of interconnected pores and channels. This unique structure provides them with a remarkably high surface area, making MOFs ideal for various applications, particularly in gas storage, gas separation, catalysis, and drug delivery.
mRNA vaccines	Core Nano	mRNA Vaccines are only possible through the development and use of lipid nanoparticles, which provide protection and targeted delivery of the mRNA particles as they are delivered to the cell. The vaccines provide cells with instructions for making proteins in order to ward off or fight disease and infection.
Nanocellulose	Core Nano	Nanocellulose is a biopolymer consisting of long chains of glucose with unique structural properties, whose supply is practically inexhaustible. Nanocellulose is a generic term used to refer to cellulose-based nanomaterials. There are three main domains of nanocellulosic materials, NanoFibrillar Cellulose, NanoCrystalline Cellulose, Bacterial cellulose.
Nanoceramics	Core Nano	Nanoceramics are structures made of ceramic materials that have been engineered at the nanoscale level and typically used in biomedicine and medical technology.
Nanoclays	Core Nano	Nanoclays are structures made up of nanoparticles of layered mineral silicates that have engineered structures at the nanoscale. The incorporation of nanoclays into polymeric systems dramatically enhances their barrier properties as well as their thermal and mechanical resistance. Consequently, nanoclays are employed in a wide range of industrial applications.
Nanocoating | Nanopaint (E.g. thermochromic and electrochromic coatings.)	Core Nano	Nanocoatings are ultra-thin layers or chemical structures that are built upon surfaces by a variety of methods, and used throughout the electronics, medical equipment, industrial manufacturing, transportation, and aerospace sectors. They are typically a fine coating or paint that incorporates nanomaterials or nanoparticles to enhance its properties and performance. Nanotechnology in these porducts often enables improvements in durability, adhesion, scratch/wear resistance, UV protection. Anti-Microbial properties, transparency control, and thermal insulation
Nanocomposites	Core Nano	Nanocomposites are composites that contain nanoscale reinforcements such as carbon nanotubes, graphene, that are produced by the mixtures of polymers with inorganic solids (clays to oxides) at the nanoscale. They are useful in various industries with particular focus and use in manufacturing.

Product Name	Category	Product Description
Nanocrystal	Core Nano	A nanocrystal is a material with a size of only a few nanometers and composed of atoms in either a single- or poly-crystalline arrangement. They are used in the manufacturing of filters that refine crude oil into diesel fuel, and they can also be applied to flexible substrates to produce solar panels.
Nanodiamonds	Core Nano	Nanodiamonds, or diamond nanoparticles, are diamonds with a size below 100 nanometers. They can be produced naturally by impact events such as an explosion or meteoritic impacts. Because of their inexpensive, large-scale synthesis, potential for surface functionalization, and high biocompatibility, nanodiamonds are widely considered in biological and electronic applications and quantum engineering.
Nanodots	Core Nano	Nanodots generally exploit properties of quantum dots to localize magnetic or electrical fields at very small scales. Applications for nanodots could include high-density information storage, energy storage, and light-emitting devices.
Nanofibers	Core Nano	Nanofibers have wide-ranging structures and typically have diameters in the order of 50–200 nm, and have a large surface area per unit mass and small pore size. Nanofibers are used in air and water filtration, textiles, and medicine. Many are carbon based.
Nanofluid	Core Nano	A nanofluid is a fluid containing nanoparticles. These fluids are engineered colloidal suspensions of nanoparticles in a base fluid. The nanoparticles used in nanofluids are typically made of metals, oxides, carbides, or carbon nanotubes. Common base fluids include water, ethylene glycol, and oil. They are most often applied for their heat transfer capabilities, particularly in electronics, pharmaceutical processes, fuel cells, and engines.
Nanoporous material	Core Nano	Nanoporous materials consist of a regular organic or inorganic bulk phase in which a porous structure is present. They are used in gas storage/sensing and biological applications such as embedding enzymes into substrates to enhance the lifetime of the reactions for long-term implants.
Nanorods	Core Nano	Nanorods are nanostructures that are the object of fundamental and applied research. Nanorods are often used in display technologies, because the reflectivity of the rods can be changed by changing their orientation with an applied electric field, and in microelectromechanical systems (MEMS).
Nanosilver	Core Nano	Due to the unique properties of silver at the nanoscale it is widely used in a number of consumer and medical products, mainly taking advantage of its high anti-microbial activity.

Product Name	Category	Product Description
Nanospheres	Core Nano	Nanospheres are the homogenous spheres in which a dispersed active compound or drug is adsorbed on the surface, or it may be entrapped within the polymeric matrix structure through the solid sphere.
Nanostructured metal	Core Nano	Nanostructured metals (with grain size below 100 nm) exhibit ultrahigh strength and hardness, making them very attractive for developing novel lightweight and energy-efficient structural components
Nanostructured silicon carbide	Core Nano	Particles or structures of silicon carbide with dimensions on the nanoscale, exhibiting unique properties such as high strength, high thermal conductivity, and exceptional electrical properties.
Nanowires	Core Nano	A nanowire is a rod-like one-dimensional structure typically measuring 2 to 100 nm in diameter that exhibit unique mechanical, electrical, thermal, and optical properties.. Nanowires have commercial applications in electronics including large aspect ratios, small active volumes, quantum confinement effects, integration in complex architectures
Nano-zeolites	Core Nano	A subgroup of zeolites that have been engineered or synthesized at the nanoscale level, typically with crystal sizes ranging from a few nanometers to a few micrometers. Zeolites have a three-dimensional, porous, and cage-like structure, which gives them unique properties and a wide range of applications in various industries, including in catalysis, absorbents, detergents, and environmental restoration
Nickel nanoparticles	Core Nano	Nickel nanoparticles are mainly used for their magnetic properties. They have been used in chemical cells, fuel cells, for solar energy absorption, as catalysts and as magnetic materials. The most promising applications for Ni-NPs are in catalysts for hydrogen fuel cells and in magnetic fluids for seal shock absorption, medical equipment acoustic adjustment, optical displays, etc.
Perovskites materials	Core Nano	Perovskite materials, particularly in the field of photovoltaics, posses excellent optoelectronic properties, ease of synthesis, and potential for low-cost solar cell applications. Perovskite solar cells have shown impressive efficiency improvements, making them a promising candidate for next-generation solar technology.
Photovoltaic cells	Core Nano	A photovoltaic (PV) cell, commonly called a solar cell, is a nonmechanical device that converts sunlight directly into electricity. Some PV cells can convert artificial light into electricity.

Product Name	Category	Product Description
Polyethylene Glycol (PEG) nanoparticles	Core Nano	PEG is used as a surface modification agent for nanoparticles to improve their stability, biocompatibility, and circulation time in the bloodstream. PEGylation slows or reduces the recognition and uptake of nanoparticles by the immune system, and they have many applications for drug delivery and imaging applications.
Polylactic-co-glycolic acid (PLGA) nanoparticles	Core Nano	PLGA is one of the most widely used polymers in nanomedicine. It is biodegradable and has been approved by regulatory authorities for drug delivery applications. PLGA nanoparticles are commonly employed for the controlled release of drugs, including anticancer drugs and vaccines.
Polymeric materials	Core Nano	Polymeric materials are used in a few bio/medical applications, including Polymeric Micelles, Polymeric Nanogels, and Polymeric Nanoparticles for gene delivery. Polymeric micelles are used for drug delivery and imaging applications. Polymeric nanogels can swell and shrink in response to external stimuli, such as temperature, pH, or light and have applications in drug delivery and targeted release. Various polymeric nanoparticles can also condense nucleic acids and protect them from degradation, facilitating their intracellular delivery for gene therapy applications.
Polysaccharide-based nanoparticles	Core Nano	Polysaccharides, such as chitosan and alginate, are naturally derived polymers used to prepare nanoparticles for biological applications. Theys are biocompatible and biodegradable, making them suitable for targeted drug delivery, gene delivery, and tissue engineering applications.
Quantum dots	Core Nano	Nanometer-sized crystals composed of semiconductor materials, such as cadmium selenide (CdSe), cadmium sulfide (CdS), or indium arsenide (InAs). Quantum dots exhibit quantum confinement effects, which arise from their small size, leading to discrete energy levels for electrons and holes, like the behavior of atoms.
Silicon oxide nanoparticles	Core Nano	Synthetic amorphous silica has been used in a wide variety of industrial and consumer applications including food, cosmetics, and pharmaceutical products for decades. Surface-modified silica nanoparticles, 20 nm in size and with a very narrow particle size distribution, have been available as concentrates in epoxy resins in industrial quantities for more than a decade.
Silver nano paste	Core Nano	A bonding material using silver nanoparticles that is useful for bonding high frequency devices (RF) that operate at high temperatures, bonding in power semiconductor chips, light emitting diodes (LEDs), dies in semiconductor lasers (LDs), submounts, and packages.

Product Name	Category	Product Description
Sputtering targets	Core Nano	Sputtering targets are materials used to produce thin films in a technique known as sputter deposition, or thin film deposition. In this process, the sputtering targets start off as a solid and is then split up by gaseous ions into small particles that form a spray and coat a material, which is called the substrate.
Titanium dioxide nanoparticles	Core Nano	Titanium dioxide nanoparticles are the most widely used nanoparticles in commercial industry and come in two main forms: rutile and anatase. In agriculture, they are primarily used for their photocatalytic properties and as nanocarriers for agrochemicals.
Zinc oxide nanoparticles	Core Nano	Zinc oxide nanoparticles have attracted great interest owing to exceptional chemical, electrical, mechanical, optical, and piezoelectric properties. It is used in cosmetics, sun care, coatings, paints and anti-bacterial.
Zirconium oxide nanoparticles	Core Nano	Nanocrystalline zirconia exhibits fundamental differences from micrometer-sized zirconia due to the nanosize effect and high surface-to-volume ratio. They possess very good chemical and photochemical stability, high refractive index, good transparency from the visible to the NIR spectral range.
Advanced wafer probe cards	Nano-tools	Specialized tools used in semiconductor testing and validation processes
Atomic force microscope (AFM)	Nano-tools	Used to measure surface topography at the nanoscale by scanning a sharp tip over a sample's surface, providing information on forces and interactions between atoms and molecules.
Atomic layer deposition (ALD)	Nano-tools	An advanced deposition technique that allows for ultra-thin films of a few nanometres to be deposited in a precisely controlled way.
Bioanalysis equipment	Nano-tools	A wide range of sophisticated instruments and tools used in the field of biological analysis and research.
Diagnostic tests (i.e. Analyte, Lateral Flow tests)	Nano-tools	Laboratory tests designed to measure and analyze specific substances in biological samples. Analyte Tests are crucial in clinical diagnostics, pharmaceutical research, environmental monitoring, and life sciences research. Lateral flow tests use nanoparticles as labels to detect the presence of specific biomolecules, such as antigens or antibodies.
Electron backscatter diffraction (EBSDs)	Nano-tools	Electron backscatter diffraction (EBSD) is a scanning electron microscopy (SEM) technique used to study materials at the nanoscale.

Product Name	Category	Product Description
Imaging mass cytometer	Nano-tools	Imaging mass cytometry is a cutting-edge technique that combines the power of mass spectrometry with spatial imaging to simultaneously analyze the molecular composition and spatial distribution of multiple biomarkers within cells and tissues.
Molecular beam epitaxy (MBE)	Nano-tools	MBE is an epitaxy method for thin-film deposition of single crystals, most widely used in the manufacture of semiconductors, and it is considered one of the fundamental tools for the development of nanotechnologies.
Nano etching tools	Nano-tools	Etching is used in nanofabrication to chemically remove layers from the surface of a sample during manufacturing.
Nanobiosensors	Nano-tools	Nanobiosensors are used for an early detection of cancer and agents such as pathogens, environmental pollutants and carcinogenic gases.
Nanoelectrospray ionization technology	Nano-tools	Combines the benefits of liquid chromatography, mass spectrometry, chip-based infusion, fraction collection, and direct surface analysis into one integrated ion source platform, to be used as frontend interface for mass spectrometry.
Nanofabrication tools	Nano-tools	Electron beam lithography (EBL) and focused ion beam (FIB) systems are used to create nanoscale patterns and structures on substrates.
Nanolithography	Nano-tools	Advanced lithography techniques, such as extreme ultraviolet (EUV) lithography and nanoimprint lithography enable the manufacturing of nanoscale structures for electronics and other applications.
Nanolithography probes	Nano-tools	Nanolithography probes use lights, charged ions, or electron beams to transfer a geometric pattern from a premade photomask to a photoresist layer, which is coated on a thin film material or the bulk of substrate.
Nanoparticle characterization instruments	Nano-tools	Various tools, such as dynamic light scattering (DLS), transmission electron microscopy (TEM), and X-ray diffraction (XRD), are used to analyze the size, shape, and structure of nanoparticles.
Nanosensors	Nano-tools	Nanosensors are sensing devices no greater than 100 nanometers, typically used to monitor chemical and physical phenomena across unreachable areas, detect biochemicals in cellular organelles, and measure nanoscopic particles across many industries/environments.

Product Name	Category	Product Description
Photomask	Nano-tools	Square plate that is coated with an opaque, transparent, or phase-shifting pattern used in semiconductors, commonly used in photolithography for the production of integrated circuits (ICs or "chips") to produce a pattern on a thin wafer of material (usually silicon).
Scanning tunneling microscopes (STM)	Nano-tools	A scanning tunneling microscope (STM) is a type of microscope used for imaging surfaces at the atomic/nano level.
Agricultural disease sensors | Bio-analytical nanosensors	Integrated nano	Nanosensors/diagnostic tools that are used to detect plant disease, humidity of the soil, pesticide residues, nutrient requirements, etc.
CMP slurries	Integrated nano	The chemical mechanical planarization (CMP) process is used to planarize both die level and wafer level topography and also to remove overfill metal and metalloid materials that serve as interconnects in an integrated circuit.
Hard Disk Drives (HDD)	Integrated nano	All modern Hard Disk Drives depend on Nanotechnology enabled production of thin-film magnetic recording media. The production involves depositing nanoscale layers of magnetic materials onto the disk platters. The smaller grains and precise control of nanoscale structures allow for more stable and higher-density data storage. Additionally, magnet-resistive read/write heads used in HDDs are also fundamentally nanotechnology.
HEPA (High Efficiency Particulate Air) filters	Integrated nano	Air filters that can trap and remove particles as small as 0.3 micrometers in size with a extremely high efficiency. These filters are commonly used in air purifiers, HVAC systems, and labratory settings.
Memory chips	Integrated nano	Memory chips are electronic components used to store and retrieve digital data in various devices, such as computers, smartphones, and embedded systems. Nanotechnology plays a pivotal role in the design and fabrication of memory chips, enabling their remarkable storage capacity, speed, and efficiency. Through nanotechnology, memory chips employ techniques like miniaturization and precise control of materials at the nanoscale to create densely packed arrays of memory cells.
Nano tape	Integrated nano	A synthetic adhesive tape consisting of arrays of carbon nanotubes transferred onto a backing material of flexible polymer tape.
Nanocapsules	Integrated nano	Nanocapsules are systems in which the drug is soluble in the core, confined to a cavity surrounded by a polymer membrane, typically used as dispersions or embedded in matrices for biomedical and materials applications.

Product Name	Category	Product Description
Nano-enabled chemical sensors	Integrated nano	Advanced sensor devices that utilize nanotechnology to enhance their sensitivity, selectivity, and performance in detecting and analyzing specific chemical compounds or gases.
Nanofertilizers	Integrated nano	Nanofertilizers are nutrients that are encapsulated or coated within nanomaterial in order to enable controlled release, and its subsequent slow diffusion into the soil.
Nanomagnetic healthcare therapies	Integrated nano	A nanomagnet is a nanoscopic scale system that presents spontaneous magnetic order (magnetization) at zero applied magnetic field. They may be used to integrate tiny particles that are directed to a particular tissue or organ for drug delivery and magnetic hyperthermia.
Nanomedicines	Integrated nano	Nanomedicines is a very broad category that applies to the application of nanotechnology in medical settings. Nanomedicines help to deliver drugs and other therapeutics treatments to targeted cells or to control the speed of uptake for certain medicines. Nanomedicines also include nanoscale diagnostic equipment, like biosensors, medial implants, vaccines, and much more.
Nanopesticides	Integrated nano	Innovative-nanopesticides are nanomaterials engineered to plant protection, minimize application losses, increase coverage on the leaf, enhance stability, and reduce the quantities of formulation's ingredients.
Optical metasurfaces	Integrated nano	Nanophotonic technology that involves the manipulation of light using arrays of subwavelength-sized structures, often referred to as "meta-atoms."
Organic light-emitting diodes (OLEDs)	Integrated nano	Organic light emitting diodes (devices) or OLEDs are monolithic, solid-state devices that typically consist of a series of organic thin films sandwiched between two thin-film conductive electrodes.
Smart pills	Integrated nano	Nanotechnology is used to develop nanomedicines such as smart pills that offer advanced functions such as imaging, sensing and drug delivery. For instance, there is the PillCam, a dose-tracking pill available with a miniature video camera.
Triboelectric auditory sensor	Integrated nano	Essentially, an ultra-sensitive microphone that constructs an electronic auditory system and an architecture for an external hearing aid in intelligent robotic applications.
Capacitors	Nano-enabled	Nanotechnology has improved some key functions and capabilities within capacitors, leading them to be smaller, higher capacitance, less energy loss, and faster reacting.
Chemical batteries (Lithium-Ion, Zinc-Air, Sodium-Ion, etc.)	Nano-enabled	Fabricated batteries employing technology at the nanoscale, which are rechargeable and use various elements and techniques to store energy.

Product Name	Category	Product Description
Closed-cell elastomeric insulation	Nano-enabled	Elastomeric insulation is a synthetic rubber composed of a closed-cell structure available in factory-made tubes, sheets, or rolls, typically used for insulation such as refrigeration piping, water lines, etc. Often nanotechnology is involved by the incorporation of nanomaterials into the insulation in order to Improve thermal insulation, improve strength and durability, create more effective barriers, adad flame retardant properties, and more.
Conductive ink	Nano-enabled	Conductive ink results in a printed object which conducts electricity, which can be used in printing RFID tags as used in modern transit tickets or to improvise or repair circuits on printed circuit boards. Some common nanomaterials used in Conductive Ink include nanosilver, nanocopper, or graphene.
Dental flowable composite	Nano-enabled	Next generation nano-technology flowable composite is low viscosity, visible light activated, and radiopaque. This dental flowable composite is versatile for an expanded range of indications and techniques. Nanoscale fillers, such as nano-sized silica or glass particles, can be incorporated into the composite resin matrix. These nanofillers improve properties like strength, wear resistance, and hardness. Nanoparticles can also be used to control the optical properties of dental composites, such as translucency and color stability,
Fuel (Additives)	Nano-enabled	Nanoparticles are being used as fuel additives to improve the overall performance of fuels. For example, metal nanoparticles, such as platinum and palladium, can act as catalysts to enhance the combustion efficiency and reduce harmful emissions in internal combustion engines.
Fuel (Catalysis)	Nano-enabled	Nanomaterials are extensively used as catalysts in fuel production processes. Catalysts with nanoscale structures offer larger surface areas and higher reactivity, resulting in better selectivity and yield during fuel synthesis. This helps in optimizing the fuel composition and improving its quality.
Fuel Cells	Nano-enabled	A fuel cell is an electrochemical cell that converts the chemical energy of a fuel (often hydrogen) and an oxidizing agent (often oxygen) into electricity through a pair of redox reactions. Used for primary and backup power for commercial, industrial, and residential buildings.

Product Name	Category	Product Description
Glass and optical coatings (e.g. Anti-fog coatings, Lens Cleaners, Gorilla Glass)	Nano-enabled	Glass and Optical Coatings, generally, provide enhanced resistance to scratching or marking and offer other properties, like hydrophobic water repellent. Anti-fog agents are nanoparticles that prevent the condensation of water in the form of small droplets on a surface that resemble fog. Lens Cleaners works on a molecular level by trapping dirt and oils in micelles and suspending them in surfactant above the surface, so all of the gunk can easily be wiped away without scratching or damaging factory coatings. Gorilla Glass is critical for most modern smart phones and touch screen enabled devices. It is more resistant to impact and scratches than earlier, conventional smartphone glass.
Light-emitting diodes (LEDs)	Nano-enabled	A light-emitting diode (LED) is a semiconductor device that emits light when current flows through it, typically used in aviation lighting, fairy lights, automotive headlamps, camera flashes, etc. Nanoscale phosphor materials are used in LEDs to convert light colors emitted by the LED chip into different spectrums, producing a different color light. These nanophosphors improve color rendering and color temperature control in LED lighting.
Logic chips	Nano-enabled	A logic chip is a microchip that is primarily designed to perform logic operations on data. It may or may not have some onboard storage space, but this does not make it a memory chip.
Lubricants	Nano-enabled	By incorporating nanotechnology, nanoscale additives, and engineered nanoparticles into lubricant formulations, companies have been able to enhance lubricant properties, reduce friction, and increase wear resistance.
Medical and protective equipment (e.g. surgical masks, nitrile gloves)	Nano-enabled	Nano-fiber based masks filter airborne chemicals and can remove volatile organic compounds, nanoparticles, and bacterial contaminants in the air, and are more effective than carbon-based air filters. Nitrile gloves are Latex-free, resistant to a range of chemicals and suitable for use within electrically sensitive applications. The gloves are made of synthetic polymers and are latex and accelerant free, reducing the potential for sensitivities and reactions in controled environments.
Membranes	Nano-enabled	Advanced filtration or separation materials that incorporate nanoscale features and engineered structures to enhance their performance and capabilities.
Nanofabric	Nano-enabled	Nanofabrics are textiles, engineered with nanoparticles or more frequently finished with coating treatments, that give ordinary materials advantageous properties such as superhydrophobicity, odor and moisture elimination, increased elasticity and strength, and bacterial resistance.

Product Name	Category	Product Description
Nanotech-based smart wearables	Nano-enabled	Nanosensors that are used to monitor patients remotely, which may be embedded in cloths to record medical data such as blood pressure, heartbeat and sweat components.
Nanotechnology based cochlear implants	Nano-enabled	Cochlear implants restore functional hearing in the majority of deaf patients, and the nanotechnology-based implants enables the gapless interface between auditory neurons and cochlear implant electrode arrays.
Nanotherapeutics	Nano-enabled	Nanotherapeutics utilize the properties of nanomaterials to alter the pharmacology of the drugs and therapies being transported, leading to changes in their biological disposition (absorption, distribution, cellular uptake, metabolism and elimination) and ultimately, their pharmacological effect.
Semiconductor chips	Nano-enabled	A semiconductor is a material product usually comprised of silicon, which conducts electricity more than an insulator, such as glass, but less than a pure conductor, such as copper or aluminum. Used in computers, smartphones, appliances, gaming hardware, and medical equipment.
Sunscreen	Nano-enabled	Some sunscreens use nanoparticles (titanium dioxide and zinc oxide) to create a substance that retains a highly effective UV light-absorbing capacity and absorbs and scatters visible light, rendering them transparent on the skin.

Appendix B – Nanotechnology Company Citations

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