THE STATE OF NANOTECHNOLOGY DEVELOPMENT

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Executive Summary

Nanoscale science and technology development has received significant attention from both the scientific and the financial community over the past two decades. Often referred to as “nanoscience” or “nanotechnology”, it describes science and engineering efforts that are carried out on the nanometer scale (in the range of 10^{-9} to 10^{-7} meters). As nanotechnology describes the scale of science and technology development and not directed to the application towards a specific industry, it has broad potential applications in the areas of medicine, life sciences, energy, telecommunications, computer sciences, and homeland security.

Further excitement in nanotechnology was fueled by the launch of the National Nanotechnology Initiative (NNI) in 2000, with the federal government committing close to US$500 million towards NNI research starting in FY 2001- a 83 percent increase in funding from the previous year. The initiative and continued federal funding for nanotechnology research reflects a consistency by the Administration in recognizing the emerging importance of nanoscience and nanoengineering.

Coverage on the potential applications of nanotechnology has received accolades from both the scientific and popular press, and has generated much hype over the potential of breakthroughs in nanotechnology in revolutionizing life as we know it. This has attracted public and private investors alike, since speculations on the societal and economic benefits of future nanotech adoptions are optimistic. More recently, the potential of nanotechnology development has also attracted the venture capital community who are interested in the future of high-risk, high-payoff R&D efforts that would be outside the time horizon of the private sector.

A large number of academic institutions and national laboratories have set up research centers that are working on multiple applications of nanotechnology including computer, telecommunications,

aerospace, medicine, energy and ecology applications. Relevant work is also being done in the private sector, as large corporations like IBM and Hewlett Packard have heavily allocated their R&D funds to nanotechnology (roughly 50 percent of their discovery budget to nanotechnology). IBM, HP and Intel have placed much of their efforts in applying nanotechnology to computing. Some start-up companies are also researching the potential of applying nanotechnology to the computer memory storage field, as well as to optical applications such as laser technologies and communication systems.

The positive hype surrounding nanotechnology has generated significant capital flow, not only allowing for R&D financing but also future market building for nanotech application in the near term. Aside from significant funding from the federal government, foreign governments and the private sector, venture capital and equity flows into nanotechnology investments were expected to reach $1 billion by 2002. Technological development and research commitments sustained by the government, academic institutions and non-profit research sector also offer reassurance to potential financial returns in nanotechnology investments.

The most important areas for nanotechnology research and investments are considered to include materials and manufacturing, nanoelectronics and computer technology, biotechnology and medicine, and environment and energy. The most exciting speculation on nanotechnology development has been attributed to the potential benefits and applications to life sciences and biotechnology, while the advances in nanomaterials and applications towards computing and electronics are the most promising. Nanotechnology also has the potential to impact energy efficiency, storage (carbon nanotubes) and production.

The vast potential applications of nanotechnology offer diverse opportunities for investments in the short-term, mid-term and long-term in a variety of potential sub-areas of nanotech development. In the near term, the most promising technologies to consider would include those related to nanomaterials and computer nanoelectronics such as the IBM Millipede (date storage technology) and the Intel 90 nm chips. In the medium term, the development of carbon nanotubes looks positive, while further advances will be expected from biotechnological, electronic and informational technologies as well as nanomaterials development.

Despite enthusiasm over nanotechnology development, the timing of full scale application is uncertain. Since nanotechnology development is still in its infancy, it will take many years of sustained investments to achieve many of the NNI’s research goals. Long-term investment, commitment and sustainable policy initiatives will be crucial to enabling technological breakthroughs and market adoption of nanotechnologies in the future.

1. INTRODUCTION

Nanoscale science and technology development has received significant attention from both the scientific and the financial community over the past two decades. Often referred to as "nanoscience" or "nanotechnology", it describes science and engineering efforts that are carried out on the nanometer scale (in the range of 10^{-9} to 10^{-7} meters). This capability to work at molecular and atomic levels has enabled the improvement in molecular organization and the development of certain material properties (such as strength, electrical resistivity and conductivity, and optical absorption),[1] which in turn has permitted the creation of products and technologies that are currently not available with microelectronics. As nanotechnology describes the scale of science and technology development and not directed to the application towards a specific industry, it has broad potential applications in the areas of medicine, energy, telecommunications, computer sciences, and homeland security.

Coverage on the potential applications of nanotechnology has received accolades from both the scientific and popular press, and has generated much hype over the potential of breakthroughs in nanotechnology in revolutionizing life as we know it. This has attracted public and private investors alike, since speculations on the societal and economic benefits of future nanotech adoptions are optimistic. More recently, the potential of nanotechnology development has also attracted the venture capital community who are interested in the future of high-risk, high-payoff R&D efforts that would be outside the time horizon of the private sector.

Further excitement in nanotechnology was fueled by the launch of the National Nanotechnology Initiative (NNI) in 2000, with the federal government committing close to US$500 million towards NNI research starting in FY 2001- a 83 percent increase in funding from the previous year. In 2003, President Bush has signed the Nanotechnology Research and Development Act, which authorizes continued funding for NNI over the next four years starting in FY 2005. The President requested $849 million for nanotechnology R&D across 10 federal agencies- a 10 percent increase over the amount requested in FY

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[1] National Research Council (2002). "Small Wonders, Endless Frontiers: A Review of the National Nanotechnology Initiative." National Research Council, Committee for the Review of the National Nanotechnology Initiative. Washington D.C. 2002. p.4.

2003.[2] The initiative and continued federal funding for nanotechnology research reflects a consistency by the Administration in recognizing the emerging importance of nanoscience and nanoengineering.

TABLE 1 - Small Technologies Milestones:

1959: Richard Feyman predicts the future of small tech in his lecture "There's plenty of room at the bottom."
1962: Honeywell develops the first MEMS pressure sensor.
1970: First MEM nozzle structures developed at Xerox.
Early 1980s: German scientists develop LIGA (lithography, electroplating and molding); establishing the Microsystems era.
1981: Invention of the scanning tunneling microscope (STM) at IBM.
1982: "Buckyballs" discovered by Richard Smalley, Robert Curl Jr. and Harold Kroto.
1986: K. Eric Drexel publishes "Engines of creation."
1990: Invention of near-field optical microscopy.
1991: Carbon nanotubes discovered by Sumio Lijima.
1993: Saab places first MEMS-based accelerometers.
1996: Nobel Prize in Chemistry for Richard Smally, Robert Curl, Jr. and
2000: President Clinton announces the National Nanotechnology Initiative (NNI).
2000: Researchers at the University of Massachusetts discover a way to cause molecules to self-assemble in a controlled fashion (tiny machines that self-replicate).
2001: IBM and HP announce breakthroughs in efforts to create molecular components for computers.
2002: IBM announces breakthroughs in memory devices: Millipede.

Source: Paul, Ziegel & Company.

Despite the enthusiasm over nanotechnology development, the timing of full scale application is uncertain. The associated risks with nanotechnologies be it societal, financial and technological, are also yet to be identified and thoroughly understood. Since nanotechnology development is still in its infancy, it will take many years of sustained investments to achieve many of the NNI's research goals. Therefore, hesitancy in substantial investments and speculation on the timing of market adoption are understandable. Nonetheless, the economic and societal potential benefits of nanotechnology applications have been widely recognized and it is encouraging to see the U.S. government taking the leadership role in directly the development of the basic nanoscale science and engineering infrastructure. Long-term investment, commitment and sustainable policy initiatives will be crucial to enabling technological breakthroughs and market adoption of nanotechnologies in the future.

2. GOVERNMENT INVESTMENTS IN NANOTECHNOLOGY

[2] Office of the Press Secretary (2003). "President Bush Signs nanotechnology Research and Development Act." Office of the Press Secretary, the White House. December 2003.

"My budget supports a major new National Nanotechnology Initiative, worth $500 million, … the ability to manipulate matter at the atomic and molecular level. Imagine the possibilities: materials with ten times the strength of steel and only a small fraction of the weight – shrinking all the information housed at the Library of Congress into a device the size of a sugar cube – detecting cancerous tumors when they are only a few cells in size. Some of our research goals may take 20 or more years to achieve, but that is precisely why there is an important role for the federal government."[3]

President William J. Clinton
January 21, 2000
California Institute of Technology

U.S. National Nanotechnology Initiative (NNI)

The National Nanotechnology Initiative (NNI) was launched during President Clinton's budget submissions to Congress in 2001, constituting an effort to create a national framework for federal-level coordination in nanotechnology R&D across agencies. The Nanoscale Science, Engineering and Technology (NSET) was established as a subcommittee of the National Science and Technology Council (NSTC) Committee on Technology (CT), and it is responsible for coordinating federal nanoscale R&D programs.[4] Funding for nanoscale science and technology from 1999 to the present is as shown below:

[3] National Science and Technology Council (2000). "National Nanotechnology Initiative: The Initiative and its Implementation Plan." National Science and Technology Council, Committee on Nanoscale Science, Engineering and Technology. Washington D.C. July 2000. p.1.

[4] Agencies that are currently represented on NSET include; the Department of Defense (DOD), Energy (DOE), Justice (DOJ), Transportation (DOT), Agriculture (USDA), State and Treasury; the Environmental Protection Agency (EPA); the National Aeronautics and Space Administration (NASA); the National Institute fro Health (NIH); the National Institute of Standards and Technology (NIST); the National Science Foundation (NSF); the Nuclear Regulatory Commission (USNRC); the Central Intelligence Agency (CIA); and two White House offices (the Office of Management and Budget (OMB) and the Office of Science and Technology Policy (OSTP)).

TABLE 2 - Nanotechnology Research and Development Funding by Agency (million US dollars)

Organization	FY 1999	FY 2000	FY 2001	FY 2002 estimate	FY 2003 estimate
National Science Foundation (NSF)	85	97	150	199	221
Dept. of Defense (DOD)	70	70	123	180	201
Dept. of Energy (DOE)	58	58	88	91	139
Dept. of Justice (DOJ)			1	1.4	1.4
Dept. of Transportation (DOT)				2	2
National Institute of Health (NIH)	21	32	40	41	43
NASA	5	5	22	46	51
Dept. of Commerce	16	8	33	38	44
EPA			5	5	5
USDA			2	1.5	2.5
TOTAL	255	270	464	604.9	709.9
(% increase from previous year)	(-)	(6%)	(72%)	(30%)	(17%)

Source: National Research Council.

The NNI funding is distributed among the federal agencies around five funding themes:[5]

1. **Fundamental Research** – long-term fundamental nanoscience and engineering research.
2. **Grand Challenges –** support for interdisciplinary research and education terms, including centers and networks that work on key long-term objectives.
3. **Centers and Networks of Excellence** – a number of centers and networks of excellences will be established each year, where these centers will play a key role in achieving top NNI priorities, in developing and utilizing specific nanoscale research tools and in promoting research partnerships.
4. **Research Infrastructure** – creating a research infrastructure for metrology, instrumentation, modeling and simulation, and facilities in supporting the R&D of nanotechnology.

[5] National Research Council (2002). "Small Wonders, Endless Frontiers: A Review of the National Nanotechnology Initiative." National Research Council, Committee for the Review of the National Nanotechnology Initiative. Washington D.C. 2002. p.13-14.

5. **Societal Implications** – studying the ethical, legal, social and workforce implications of nanoscale science and technology, while supporting workforce education and training in nanotechnology.

The NNI has been successful thus far in establishing a concerted effort at the federal level to direct nanotechnology development in the United States, with initiatives to articulate both near-term and long-term strategies and goals to implement specific R&D programs in nanoscience and nanoengineering. The creation of the NNI has given solid grounding to the growth of the nanotech industry, and has served as a catalyst in sparking private interests in nanotech development. The U.S. government has allocated over $1.3 billion to nanotechnology in the past two years, with significant portion of the funding dedicated to infrastructure building at academic institutions. In September 2001, the National Science Foundation (NSF) awarded six grants totally $65 million to six university nanoscience research centers: Columbia University, Cornell University, Rensselaer Polytechnic Institute, Harvard University, Northwestern University and Rice University.[6] These centers of excellence are expected to provide substantial portion of the basic research needed to facilitate nanotech advancements and in industry building activities.

International Nanotechnology Development Activities

Although the United States is currently leading in nanoscale science and technology development, the international community has also very actively participated in the nanotech race. Worldwide, investment in nanotechnology development has more than tripled between 1997 ($432 million) and 2001 ($1619 million) particularly amongst economically developed countries (with Japan, and the European Union being the most aggressive in nanotechnology investments outside the U.S.).

[6] Juan F. Sanchez (2002). "Nanotechnology: "Tremblor to Tsunami: Visible Today; Inescapable Tomorrow." Punk, Ziegel & Company. New York City. August 2002. p.20.

More than thirty countries have government funded programs in nanoscience and engineering, with the U.S. National Nanotechnology Initiative (NNI) as the largest in the world.[7]

TABLE 3 - Estimates for Government Nanotechnology R&D Budgets (million US dollars)

Area	2000	2001	2002 Preliminary
Western Europe	200	225	400
Japan	245	465	750
United States	270	422	604
Other	110	380	520
Total	825	1,492	2,274
(% of 2000)	(100%)	(181%)	(276%)

Source: National Research Council.

3. PRIVATE INVESTMENTS AND OPPORTUNITIES IN NANOTECHNOLOGY

The early stages of infrastructure building of the nanotech industry have already affected a broad range of industries. A large number of academic institutions and national laboratories have set up research centers that are working on multiple applications of nanotechnology including computer, telecommunications, aerospace, medicine, energy and ecology applications. Relevant work is also being done in the private sector, as large corporations like IBM and Hewlett Packard have heavily allocated their R&D funds to nanotechnology (roughly 50 percent of their discovery budget to nanotechnology)

[7] National Research Council (2002). "Small Wonders, Endless Frontiers: A Review of the National Nanotechnology Initiative." National Research Council, Committee for the Review of the National Nanotechnology Initiative. Washington D.C. 2002. P.26.

* Countries involved in nationally sponsored nanoscale technology development centers include: the United States, members states of the European Union, Canada, Taiwan, Korea, China, Australia, Japan, Israel, and Romania.

while other companies such as Mitsubishi, Motorola and Lucent Technologies have also aggressively invested in nanotechnology research.[8]

IBM, HP and Intel have placed much of their efforts in applying nanotechnology to computing. IBM's Zurich Research Lab has recently made a breakthrough in apply nanotech to computer memory storage, with the construction of a 1,024 "leg" millipede for storing and retrieving high-density data.[9] It is believed that the development of the millipede could potentially increase the density of hard disk drives by a factor of 40. Products based on these new techniques could reach the market in 2 to 3 years. IBM is also the leader on the development of carbon nanotubes, of which the potential application could surface in the next 3-5 years.[10] Intel has continued its work on its silicon lead, developing a 90 nanometer process beyond 0.13 micron on its latest silicon chip. These latest development in nanotech application can dramatically alter the computer industry in the near future.

A number of start-up companies have also entered the field, the best-known of which includes Zyrex, NanoDynamics, Nanosys, NanoMateria, Imago Scientific Instruments, Molecular Imprints, NanoInk, Nanosphere, Nantero and ZettaCore. Solid commitment to building foundations for the nanotech industry by the federal government and the private sector, combined with the hype surrounding nanotech development have been able to lower some of the barriers to entry generally associated with new technologies. The positive hype surrounding nanotechnology has also generated significant capital flow, not only allowing for R&D financing but also future market building for nanotech application in the near term. Aside from significant funding from the federal government, foreign governments and the private sector, venture capital and equity flows into nanotechnology investments were expected to reach

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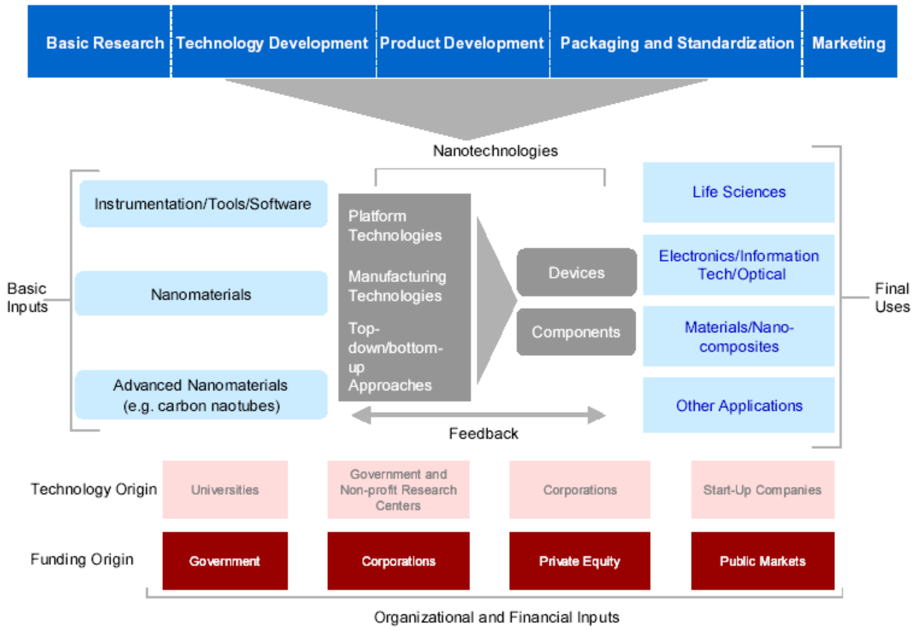
[8] Juan F. Sanchez (2002). "Nanotechnology: "Tremblor to Tsunami: Visible Today; Inescapable Tomorrow." Punk, Ziegel & Company. New York City. August 2002. p.9.

[9] Steven Milunovich (2003). "Still the Next Small Thing: Nanotechnology Refresher." Merrill Lynch & Co. Global Securities Research & Economics Group. November 2003. p.3.

[10] Ibid. p.4.

$1 billion by 2002.[11] It is estimated that there are currently over 50 venture capital firms with active investments in nanotechnology, including Draper Fisher Jurvetson, Tuva Capital Partners and a fund created by Eli Lilly.[12]

Nanotechnology Industry Framework



Source: Paul, Ziegel & Company.

Since the market potential and timing for the realization of nanoscale science and engineering potentials are still uncertain, financial commitments made by the federal government and venture capitalists are particularly important in shaping the investment landscape for nanotechnology in the long run. On the same note, technological development and research commitments sustained by the government, academic institutions and non-profit research sector also offer reassurance to potential financial returns in nanotechnology investments. The most promising areas of nanotechnology

[11] Steven Milunovich (2001). "TechStrat Conference: Nanotechnology is the Future." Merrill Lynch & Co. Global Securities Research & Economics Group. October 2001. p.12.

[12] Juan F. Sanchez (2002). "Nanotechnology: "Tremblor to Tsunami: Visible Today; Inescapable Tomorrow." Punk, Ziegel & Company. New York City. August 2002. p.23.

breakthroughs including nanobiotechnologies, and electronic, mechanical and optical devices may take up to twenty years to realize, while the associated investment costs and risks are also likely to be higher.

4. NANOTECHNOLOGY'S IMPACT AND MARKET APPLICATIONS

As mentioned previously, the potential for nanotech products and services applications are vast, spanning across a wide range of industries and disciplines. The most important areas for nanotechnology research and investments are considered to include materials and manufacturing; nanoelectronics and computer technology; biotechnology and medicine; and environment and energy.

Materials and Manufacturing

Nanomaterials are nanoscale material that exhibit new and/or certain properties that will act as building blocks upon which complex two- and three-dimensional functional nanoscale systems with the built, enabling new devices and new functionalities.[13] Benefits of nanostructuring can result in lighter, stronger and programmable materials, enabling unique applications such as high-speed integrated circuits, and the use of molecular/cluster manufacturing to develop structures and architectures that did not exist previously in nature.

Inorganic nanomaterials such as nanotubes, ceramic, powers, nanocrystals are being intensely developed. Recent efforts also include synthesis of organic or bio-inspired materials such as organic nanofibers that mimic collagen fibers. Moreover, hybrid materials such as carbon nanotubes are considered as advance nanomaterials that exerts particular qualities that make these structures suited for a variety of applications ranging from replacing current TV and computer monitors, computer memory devices, conductivity and storage, and are also being considered for the storage of hydrogen.[14]

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[13] National Research Council (2002). "Small Wonders, Endless Frontiers: A Review of the National Nanotechnology Initiative." National Research Council, Committee for the Review of the National Nanotechnology Initiative. Washington D.C. 2002. P.36.

[14] Ibid. p.38.

TABLE 4 - Nanomaterials Applications

• **Composites and traditional materials** Coatings (aerospace, automotive, consumer goods) Paint additives, adhesives, sealants Anti-corrosives Apparel Fillers Aerospace/automotive composites Plastic and metals • **Energy/Environmental** Nanoparticle catalysts Fuel Cells, Solar Cells Light Sources (LEDs, nanotube-based bulbs) Filtration Chemical sensors	• **Life Sciences** Cosmetics Drug delivery Materials for tagging and screening technologies Composites for devices • **Electronic/information technologies** Composites for memory chips, microprocessors Optical materials (flat panel devices) Sensors Lasers Composites for electronic devices

Source: Paul, Ziegel & Company.

Nanoelectronics and Computer Technology

The continuing development in the field of Integrated Circuits (IC) and semiconductors has been inching closer to maturity with currently available technologies. There has been increasing demand for greater precision and more advanced materials other than silicon to be developed to improve capabilities, size and performance. Nanoelectronics advances could potentially open future markets for nanotechnology semiconductors/microprocessors, as carbon nanotubes are being seriously considered to replace silicon in transistors. Moreover, some start-up companies are also researching the potential of applying nanotechnology to the computer memory storage field, as well as to optical applications such as laser technologies and communication systems.

Biotechnology and Medicine

The most exciting speculation on nanotechnology development has been attributed to the potential benefits and applications to life sciences and biotechnology. The ability to manipulate molecular behavior and structures at nanometer scales has revolutionary implications for the disciplines of chemistry, physics and biology. Using nanobiotechnology to master techniques to manipulate biological and non-biological elements at the molecular and atomic level will increase the speed and quality of genome sequencing for gene tracking and diagnostics and therapeutics. Consequently, nanotechnology can facilitate the development of tools for diagnostic and biochemical research, for medical and surgical equipments and technologies, and new formulations for drug discovery, design and delivery. It is estimated that in 15 years approximately 50 percent of bio-pharmaceutical methods for drug discovery and manufacturing will rely on nanotechnology.[15] Increased capabilities to study cell biology and pathology can also improve early detection and treatment of diseases, such as the detection of cancerous cells/tumors.

Environment and Energy

Nanotechnology has the potential to impact energy efficiency, storage (carbon nanotubes) and production. The adoption of nanotechnology in industrial practices has the potential for energy savings through the development of technologies and processes that curb emissions from a wide range of sources, minimize the generation of undesirable by-products, and substituting environmental undesirable products with eco-friendly materials generated by nanotechnology (replacement of carbon black in tires by

[15] Juan F. Sanchez (2002). "Nanotechnology: "Tremblor to Tsunami: Visible Today; Inescapable Tomorrow." Punk, Ziegel & Company. New York City. August 2002. p.16.

nanoscale particles of inorganic clays and polymers that lead to the production of environmentally friendly, wear-resistant tires).[16]

5. NANOTECHNOLOGY DEVELOPMENT TIMELINE

The vast potential applications of nanotechnology offer diverse opportunities for investments in the short-term, mid-term and long-term in a variety of potential sub-areas of nanotech development. Understanding of the investment timeframes, the embryonic nature of many aspects of nanotech development and the science behind the technologies themselves are therefore important considerations for investors and the financial community.

In the near term, the most promising technologies to consider would include those related to nanomaterials and computer nanoelectronics such as the IBM Millipede (date storage technology) and the Intel 90 nm chips. In the medium term, the development of carbon nanotubes looks positive, while further advances will be expected from biotechnological, electronic and informational technologies as well as nanomaterials development. In the long term, substantial development will be expected from all aspects of nanoscience and nanoengineering, in particular with breakthroughs in molecular electronics and quantum computing systems.

TABLE 5 - Nanotech Timeline

Short Term	0-2 Years	IBM Millipede, Intel 90 nm chips
Medium Term	3-5 Years	Carbon nanotubes, organic memory chips
Long Term	5-10 Years	Bottoms-up quantum systems
Extended Term	10-50 Years	Molecular electronics, quantum computing
Never	50+ Years	Self-replication, artificial consciousness

Source: Merrill Lynch & Co.

[16] National Science and Technology Council (2000). "National Nanotechnology Initiative: The Initiative and its Implementation Plan." National Science and Technology Council, Committee on Nanoscale Science, Engineering and Technology. Washington D.C. July 2000. p.23.

It has been argued that the adoption of new technologies and its market application generally takes about 25 years to become widely accepted.[17] Moreover, it is also common to both underestimate and overestimate the time frames for which technology advances and development. Given these timing uncertainties, nanoscale science and engineering could become the next technological revolution although when this will happen is still to be speculated.

6. MARKET PROSPECTS AND RISKS

Market conservatives argue that the timing environment of nanotechnology is still too early for substantial investments. It is therefore to be expected that it will take some more time for nanotechnology R&D to move forward and closer to market commercialization before higher levels of investments in nanotechnologies will take place. However, the importance of nanotechnology should not be overlooked. It is expected that nanoscience and engineering development will impact nearly every industry (chemical, computing, storage, power, energy, biotech, pharmaceuticals, manufacturing and transportation). Immediate applications are already present with the breakthroughs in computer memory processors technologies (millipedes) and carbon nanotubes. The National Science Foundation predicts that the market for nanotechnology products and services in the U.S. will conservatively reach $1 trillion by 2015.[18]

Given all its hype and development, it is also important to evaluate the societal implications of nanotechnology advancements. Powerful technologies bring benefits as well as negativities, and therefore further research, education and public policies should be dedicated to study the possible negative impacts and explore channels to reduce risks associated with nanotechnology.

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[17] Steven Milunovich (2001). "TechStrat Conference: Nanotechnology is the Future." Merrill Lynch & Co. Global Securities Research & Economics Group. October 2001. p.2.

[18] Ibid. p.10.

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