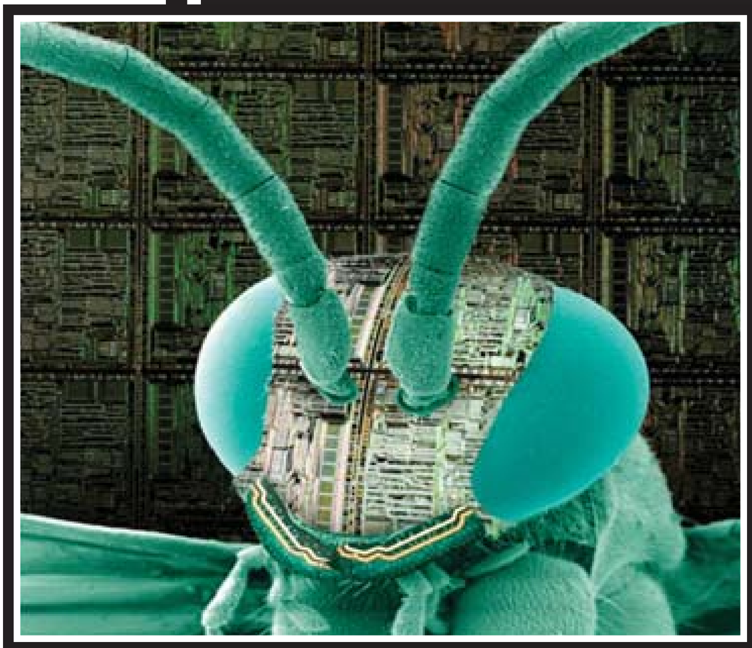
Future Issue

Nanotechnology



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Nanotechnology

Nanotechnology in Brief

Nanotechnology is widely considered to be 'the' technology of the future with applications in – and implications for – a wide range of fields such as, a.o, healthcare & medicine, material manufacturing, energy extraction and the conduct of warfare. Global investment in nanotechnology-related R&D has surged over the years and currently stands at over $25 billion dollar. Yet, many uncertainties surround the role of 'nanotech' in the future. Will its impact be evolutionary or revolutionary? Does nanotech harnass a threat to mankind – as some science-fiction writers claim – or does it provide solutions to problems faced by humanity across a variety of fields? The current Future Issue addresses these questions and others while examining trends, exploring drivers and explaining how developments in nanotechnology may shape the security environment of the future based on an in depth analysis of 59 foresight studies. The security implications of nanotechnology are diverse. Breakthroughs in nanotechnology may herald the birth of a new generation of weaponry rendering large parts of the existing stockpiles of conventional 'old' arms obsolete. While it is unclear whether this will ignite an arms race between great and medium powers in the international system, it will definitely alter the level-playing-field between those states that are able to reap the benefits of the nanotechnology revolution and those that are not. Apart from nanotechnology's impact on the geostrategic level, implementation of nanotechnology applications may change the ways in which militaries plan for and fight wars and lead to a revolution in the tactics employed in military operations. Terrorist actors will probably seek to use nanotechnology applications to commit deadlier attacks, but it is likely that the capacity of homeland security departments to detect terrorist actions will be strengthened as well. In sum, developments in nanotechnology will provide both threats and opportunities for governments and industry which should be taken into account in long term strategic planning processes.

Indicators
Impact of nanotechnology, level of interest, public tolerance, dominant actor, nature of government participation, source of regulation, economic potential, market diversity, application diversity.
Drivers / Underpinning Mechanisms
Nano experience, social concerns, economic competition, technical concerns, human capacity, problem solving potential, research & scientific capacity, funding & investment.
Impact on Security / Business
Issues of access, conflict prevention, arms race, stability, deterrence, nanoweapons, human augmentation, terrorism, homeland security, revolution in military strategy.

Nanotechnology, often understood as technology operating on the scale of 1-100 nanometers, is considered by many as one of the most promising emerging technologies. As with many other technologies in this category, the precise definition of nanotechnology continues to be a point of contention. The most common approaches to defining nanotechnology can be captured under two broad headings: the top-down approach of decomposition and the bottom-up approach of synthesis. The former defines nanotechnology as manipulation, measurement, and investigation of materials at the nano-scale, whereas the latter defines it as the creation, construction, and manufacturing of products by assembling individual atoms and molecules at the nano-scale.

Despite the definitional differences, nanotechnology has become a "hot" research topic. Currently, the United States, the European Union (EU), and Japan conduct the majority of the nanotechnology research, but China, South Korea, Ireland, and Israel are emerging powers in the field. Since 1997, nanotechnology has seen substantial worldwide increases in public funding, the number of filed patents, and the number of published research papers (see figures 1-3).

These increases are likely to be the results of scientific competition, return on scientific investment, and the realisation by governments and businesses that nanotechnology is more than just a hype.

Despite the depicted trends, the future of nanotechnology remains fairly uncertain. Currently, the field is divided over the potential of nanotechnology. The proponents contend that it will offer enormous benefits and facilitate revolutionary

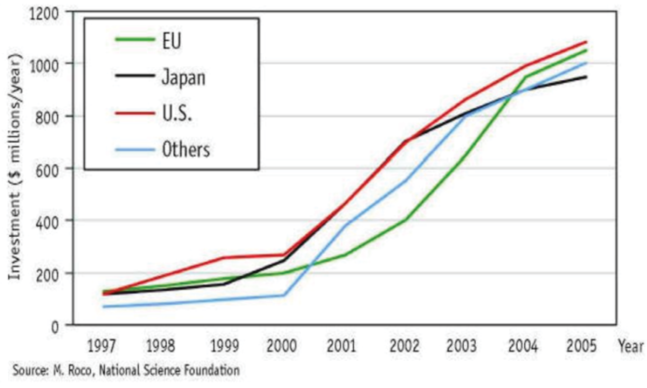
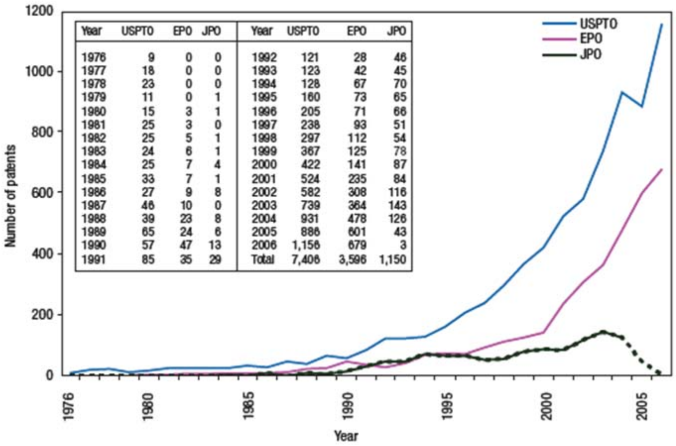


Figure 1: Worldwide Nanotechnology Funding 1997-2005

changes within society. Many others agree with this assertion; however, they caution against the development of nanotechnology because of its adverse health and environmental potential. Finally, a third group maintains that nanotechnology will not meet its “hyped-up” expectations on account of various factors (e.g. public disapproval, scientific difficulties, etc.).

Some of the most recent research areas in nanotechnology include tissue engineering, fuel cell and solar energy, water filtration,and food production. Other areas, such as electronics, drug delivery, and materials, that have traditionally been part of nanotechnology research, continue to see scientific progress.



Year	USPTO	EPO	JPO	Year	USPTO	EPO	JPO
1976	9	0	0	1992	121	28	46
1977	18	0	0	1993	123	42	45
1978	23	0	0	1994	128	67	70
1979	11	0	1	1995	160	73	65
1980	15	3	1	1996	205	71	66
1981	25	3	0	1997	238	93	51
1982	25	5	1	1998	297	112	54
1983	24	6	1	1999	367	125	78
1984	25	7	4	2000	422	141	87
1985	33	7	1	2001	524	235	84
1986	27	9	8	2002	582	308	116
1987	46	10	0	2003	739	364	143
1988	39	23	8	2004	931	478	126
1989	65	24	6	2005	886	601	43
1990	57	47	13	2006	1,156	679	3
1991	85	35	29	Total	7,406	3,596	1,150

Figure 2: Number of Patents 1976-2006

This increasing international attention, coupled with its uncertain future, creates a new worldwide technological phenomenon that carries a multiple of implications for tomorrow’s security, both in a traditional and a nontraditional sense. For this reason, HCSS collected and added 59 nanotechnology-specific foresights studies published since 1991 to its Metafore database in order to examine the foresights’ community outlook on the role of nanotechnology in the future.

This Future Issue summarises the major insights derived from these foresight studies in five main sections: a meta-analysis of global nano-related foresight studies; an evaluation of the main nanotechnology-parameters subject to change over the next decades; an examination of the drivers fuelling those changes; a look at four possible “future worlds” of nanotechnology; and an analysis of the implications of nanotechnology for security.

Meta-Analysis of the Foresight Studies on Nanotechnology

Trends in Foresight Studies

HCSS first determined which (technological) fields were discussed in the foresights and what type of source produced these foresights (e.g. government, commercial, academic, etc.). HCSS identified eight important fields (based on research and application direction) within the nanotechnology realm. These fields are listed below and some key applications are detailed in appendix A.

Nanotech Areas

1. **Health & Medicine**
2. **Materials**
3. **Environmental**
4. **Energy**
5. **Electronics**
6. **Information and Communications Technology (ICT)**
7. **Manufacturing**
8. **Security**

HCSS mapped the number of foresights per technological area per year. In doing so, HCSS aimed to determine if the individual fields had constant levels of attention or if interest in a particular field had spiked/waned. The findings from this endeavour are shown below in figure 3.

Interest in the foresight community in nanotechnology is growing across the board. Yet, there is a distinct differentiation between the technological fields of high interest and all others within nanotechnology discipline. The foresight studies emphasize the health and medicine, materials, environment, and energy fields in particular. While there are relatively few foresights specifically on the nanotechnology and security, nanotechnology is discussed relatively often in relation to security in other fields. With

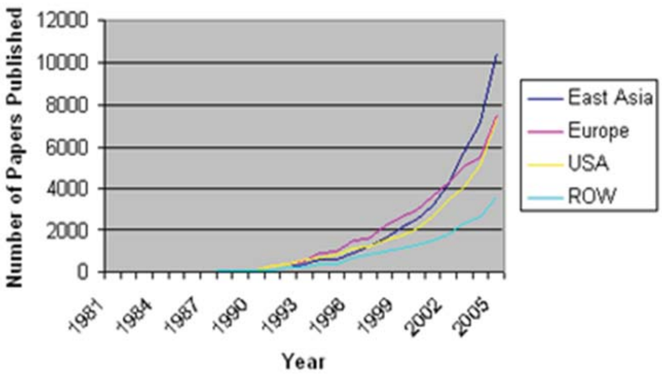
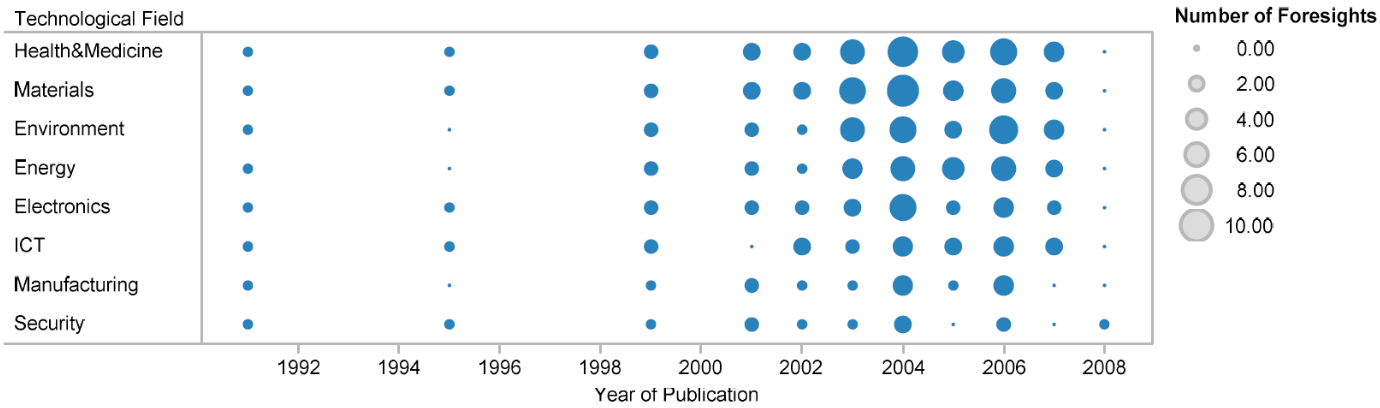


Figure 3: Number of Papers 1981-2005

Nanotechnology



Year of Publication for each Technological Field. Size shows details about Number of Foresights .

Figure 4: Nanotechnology in Eight Fields: 1992-2008

the exception of security, every technological field experienced increasing levels of attention.

Robust Findings

What do the various 'Nanotechnology Futures' that emerge out of these foresight studies look like? To answer this question, HCSS analysed the aforementioned foresight studies in search of 'robust' findings - i.e. insights about nanotechnology's future that would be found back in a large set of foresight studies and could therefore be said to be (more) reliable. These insights were coded into nine individual parameters below (see appendix B for a detailed description). These parameters were valued on a 1-3 scale, with 3 indicating a future world in which nanotechnology has a better chance to thrive. To give an example: if in one particular scenario nanotechnology was truly regulated by the free market, it was scored as a '3' on the source of regulation parameter. In this manner, a list of the most relevant parameters was created (see below) and the foresight community's assessment of the values of these parameters were mapped (see figure 5).

Parameters

1. Impact of Nanotechnology
2. Level of Interest
3. Public Tolerance
4. Dominant Actor
5. Nature of Government Participation
6. Source of Regulation
7. Economic Potential
8. Market Diversity
9. Application Diversity

The foresights generally foresee a medium level of government participation and high degrees of economic potential (profitability), market diversity (wide-ranging markets – not niche), and application diversity (many different nano-enabled products). Agreement in the foresights suggests a clear, or possibly less clouded, vision of how these parameters will develop in the future. On the other hand, the lack of a clear frontrunner in many of the social and institutional parameters reveals more uncertainty in these areas.

With the exception of "public acceptance" and "source of regulation", the foresights view the future unfolding in a manner more favourable than not to nanotechnology. This means the general picture that emerges is one in which nanotechnology has some sort of revolutionary impact (sectorally or socially); a medium to high level of public interest; with markets as dominant actors in nano-related R&D, or at the very least partnered with states; governments issue technology strategies; a profitable economic outlook, and a wide-range of markets for a diversity of nano-enabled products.

When analysed on a more aggregate level, the foresights concur about the direction of change in economic (profitable and diverse), technical (diverse), and institutional (industry-governments partnership) terms, but they cannot seem to reach agreement on how the social parameters will generally unfold.

Main Drivers

After establishing the parameters, the drivers were identified that brought about changes in the parameters. Again, the foresights offered valuable insights. From them, nine drivers were derived (see below) and appendix C for a detailed description.

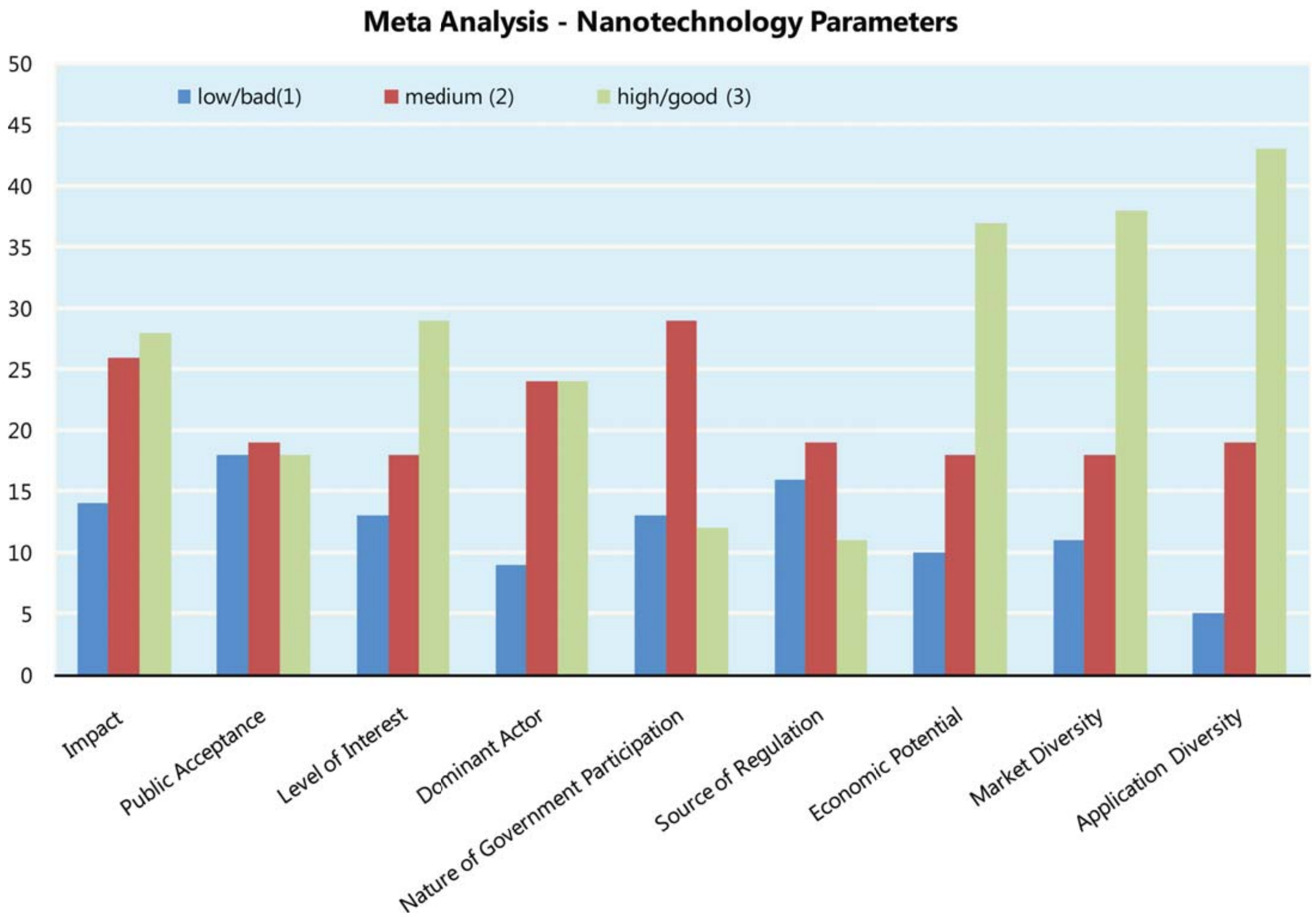


Figure 5: Meta-Analysis Nanotechnology Parameters

Drivers

1. "Nano Experience"
2. Social Concerns
3. Economic Competition
4. Technical Concerns
5. Human Capacity
6. Problem Solving Potential
7. Commercialisation
8. Research & Scientific Capacity
9. Funding & Investment

With drivers established, an assessment was made of the amount of emphasis placed on individual drivers. This was done by noting how many foresights utilised an individual driver. Furthermore, it was determined if the nano-impeding drivers ("nano experience, social and technical concerns) occurred more or less frequently than the nano-enabling drivers. The findings are shown in figure 6. Note that the nano-impeding drivers are coloured red and the nano-enabling drivers are coloured green. Funding & Investment (45) and Research & Scientific Capacity (42) are the single most important drivers while Commercialisation (34) and Problem Solving Potential (33) occurred frequently as well. Funding & Investment is the key driver because it fuels the other high frequency drivers. It provides the means for research, which paves the wave for commercialisation. Without products, there is no potential for technical concerns or problem solving potential. Essentially, funding and investment is the match that sparks the "Big Bang." More foresights considered the drivers that are responsible for getting nano-enabled products to the market than those that generally impede the development of nanotechnology. It is interesting to note that the problem solving potential drivers occur more often than those addressing public concerns. This suggests that future potential demands more consideration in the public's decision-making calculus than concern. For example, the foresights note that if nanotechnology is believed to have the ability to solve a major problem (e.g. cancer, energy crisis, etc.) that the public is usually willing to forego some of its concerns.

Since most nanotechnology funding is in the form of research funding, the funding & investment and research & scientific capacity drivers are likely to be correlated. In the short term, business opportunities are to be found in the creation of strategic partnerships between private and public actors to attract research funding. Companies with a medium/long term interest in the outcome of the nanotechnology revolution will, in addition to their R&D efforts, have to pro actively address public concerns using advertisement campaigns in collaboration with governments to inform the general public about nanotechnology. If launching a nanotechnology product prematurely would cause a major or even a minor incident it could severely impact on the public's perception of nanotechnology and offset public demand for nanotechnology for considerable amounts of time.

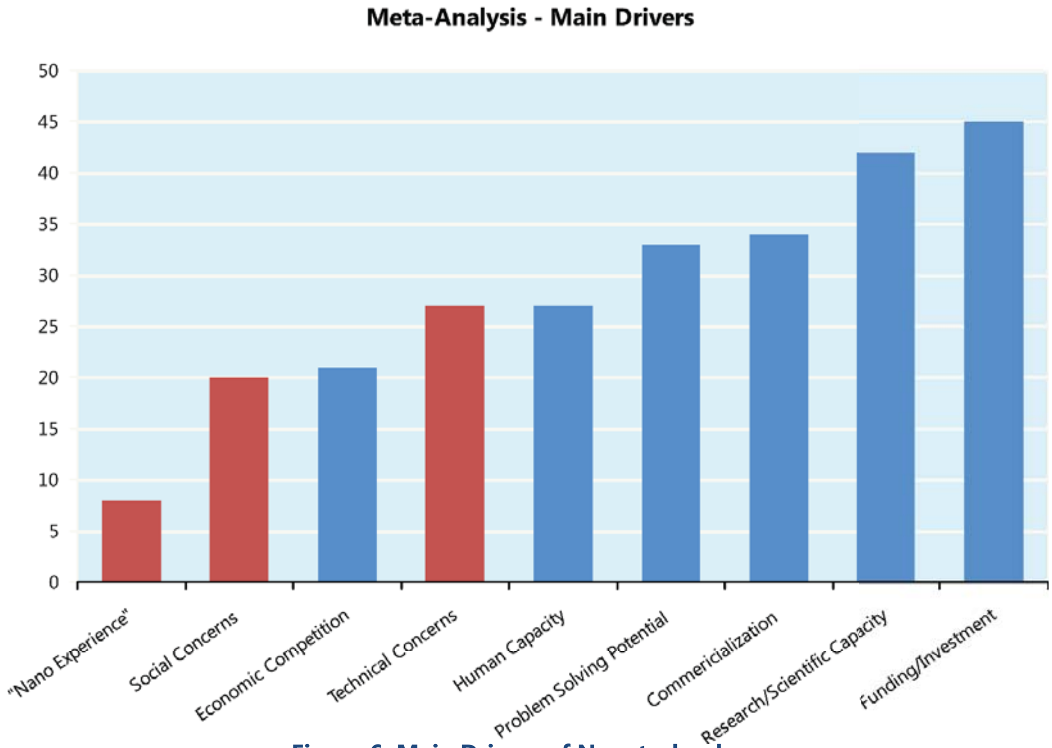


Figure 6: Main Drivers of Nanotechnology

On the other hand, as previously noted, if a major breakthrough would be achieved through a nano-enabled product, it could boost public faith in and support for nanotechnology. These are all issues that companies should take into account in their long term strategic planning.

Four Futures of Nano Technology

The analysis of the drivers and the parameters reveals that the future of nanotechnology could vary tremendously, resulting from different combinations of drivers that shape developments in nanotechnology. Drivers such as "nano experience," social concerns, and technical concerns are determinants of public acceptance of nanotechnology. A disaster with great societal damage caused by nanotechnology could create high level of concerns about the health and environmental risks posed by nanotechnology and the level of public acceptance of nanotechnology will be low.

The following section will sketch four scenarios to facilitate understanding of the interaction between the drivers and the parameters. These scenarios are not meant to be predictive of what the future will look like, but are rather specific aggregations of the foresight analyses that illustrate the different ways in which the future may unfold (figure 7).

Nano Defies Adam Smith

The "Nano Defies Adam Smith" scenario envisions a future world characterised by a partnership between governments and industry aimed at developing nanotechnology. The government provides direction by issuing a national nanotechnology strategy, and it implements both state-run and market-based initiatives to see that its strategic milestones are fulfilled. Furthermore, the government chooses to regulate nanotechnology development in conjunction with industry. This hybrid top-down/bottom-up regulatory regime sets stricter standards than those of the free market. This not only safeguards against the occurrence of nano-accidents but also boosts public tolerance by assuaging concerns associated with nanotechnology. With the public opposition barrier somewhat lowered, government and industry are able to commercialise a wide variety of products for a diverse set of markets (e.g. flexible solar panels, fuel cells, nano-scale sensors, etc.). This lays the groundwork for diffusion throughout society and institute revolutionary changes.

Nano - The American Way

"Nano – The American Way" is a fairly optimistic future nanotechnology world. This scenario begins with a government choosing to increase its domestic nanotechnology capabilities in an economically liberal manner. The government drafts an over arching technology strategy but leaves it entirely to the market to implement the strategy. In order to get the market's

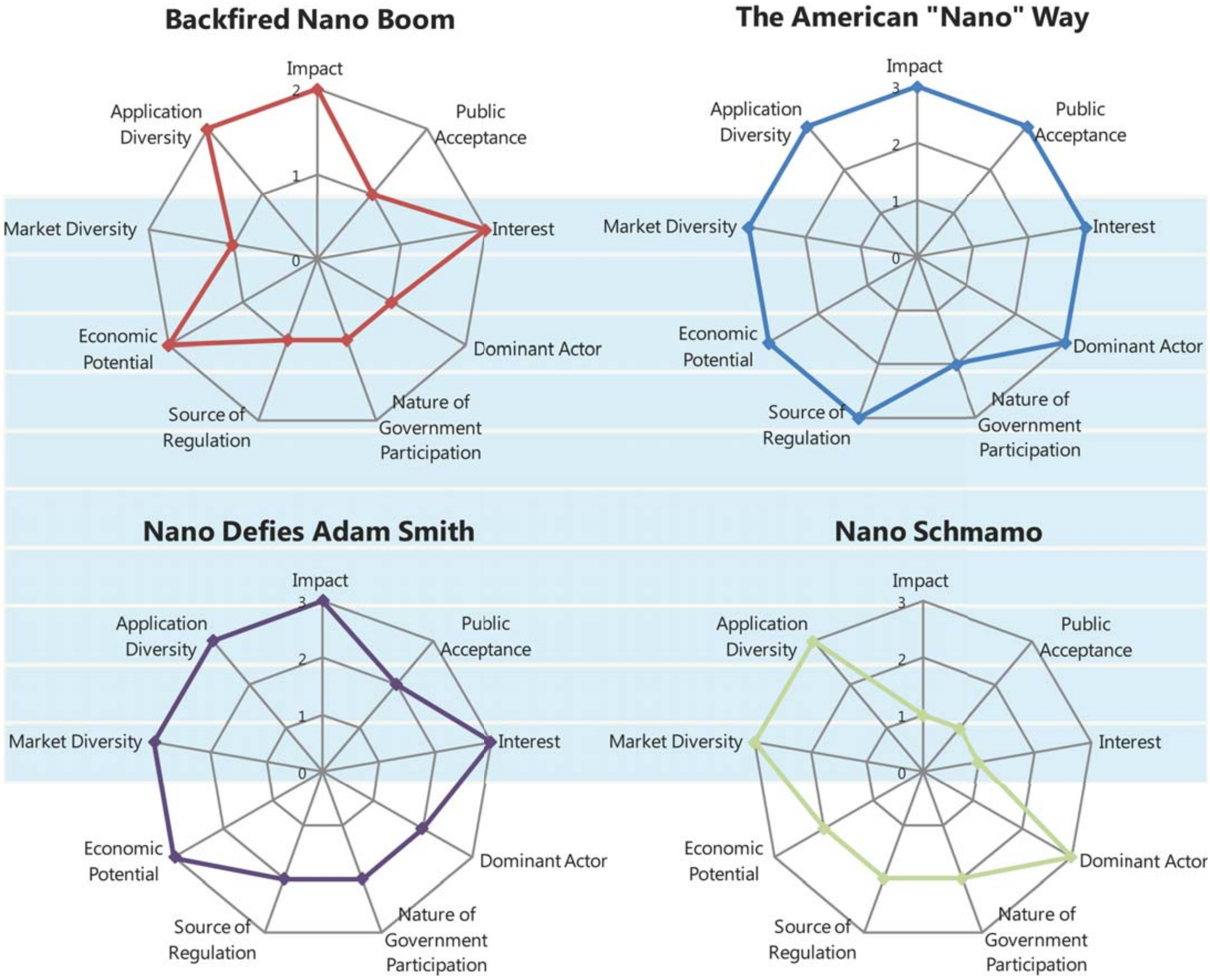


Figure 7: Four Futures of Nanotechnology

compliance, the government offers lucrative research contracts and lets competition run its course. Over time, this competition results in the development of several useful applications (e.g., targeted drug delivery, nano-scale health monitoring, etc.) and paves the way for a number of key breakthroughs (e.g., a cure for cancer) that substantiate the earlier hype surrounding nanotechnology. In turn, this boosts interest in nanotechnology.

The success of nanotechnology is the result of the pleasant "nano experience" (e.g. no nano-accidents) enjoyed by the public, which serves to assuage concerns over potential technical and social problems associated with nanotechnology. The combination of these factors enables nanotechnology to permeate society and offers the prospect of significant economic opportunity as well as revolutionary social change.

Backfired Nano Boom

A backlash against nanotechnology characterises "Backfired Nano Boom." Generally, this scenario is preceded by a "nanotechnology golden age" in which science and industry have a free hand and nano-enabled products are in high demand. The golden age ends when catastrophe strikes (nano-WMD, nano-accident, nano-crime, etc.). This experience captivates the public's attention and causes societal tolerance towards nanotechnology to plummet. Increased pressure leads governments to assume a dominant role in nanotechnology development. Once in this role, they institute strict regulations, albeit as a reactionary response, on nanotechnology and issue restrictive mandates to industry. The government decides against banning nanotechnology altogether because during its golden age significant advances were made in addressing key global problems. As a result, government restricts industry to only developing applications in the fields of health & medicine, environment, and energy. Within these areas, there is ample potential for profit and the arrival of a new nanotechnology revolution. Elsewhere, however, the opportunities are barren.

Nano Schmamo

"Nano Schmamo" represents a world in which nanotechnology has fallen well short of its advertised potential. Industry fulfils its obligations by commercialising a number of nanotech products for a wide-variety of markets. Despite providing national nanotechnology strategies and implementing minimally invasive regulations, governments generally keep themselves in check and allow the free markets to drive nanotech development. The public, however, remains unwilling to accept the risks of nanotechnology on account of concerns regarding privacy, health, and environmental safety. Furthermore, nanotech fails to deliver the promised solutions to pressing global problems (e.g. cancer, global warming, energy shortage etc.). As such, the public lacks an incentive to support nanotech initiatives or purchase nano-enabled products. This adversely impacts the profits derived from nanotechnology and hinders innovation. Without the latter, industry cannot develop the promised nano-products and, consequently, energise the public. The overall impact of nanotechnology on society remains therefore low, and its applications are relegated to the status of "improvement" technologies.

Security Applications

HCSS also explored the security implications of nanotechnology. The foresights were used first to determine which applications of nanotechnology are likely to be employed in the realm of security. After a brief analysis of the applications, the implications of these technologies were examined on the levels of field applications, national security strategies, strategic interaction among nations, and the international strategic environment.

The subset of public-domain nanotechnology foresights discussing security applications was rather limited. As a result, only a quarter of the nanotechnology foresights gathered by HCSS were usable in assessing security applications. Despite this caveat, the team found eight applications that appeared in a third or more of the security-related foresights. They are depicted in figure 8..

CBRN Agent Detection

Systems specifically designed to detect chemical, biological, nuclear, and radiological agents using nanoporous materials.

Targeted Drug Delivery

Targeted drug delivery concerns the delivery of small packets of medicine to afflicted parts of the body. The foresights envision this application being combined with health monitoring, sensors, and smart materials in order to form a "self-medicating" uniform for soldiers.

Surveillance & Sensors

"Surveillance & Sensors" is a combination of nanoscale information gathering applications such as weapons equipped with sensors to monitor condition and ammunition levels.

Nano Uniforms

Nano uniforms are applications of nanotechnology that seek to provide the soldier with increased camouflage capabilities. However, more advanced versions of the suit can incorporate health monitoring, CB agent protection and anti-ballistic material.

CB Agent Remediation

This is an application that has nanoparticles chemically bind with and neutralize chemical and biological pathogens.

Enhanced Materials

"Enhanced materials" is a combination of applications that take advantage of the improved material qualities of nanotechnology (e.g. nano-enabled anti-ballistic material, nanocomposite plastics, stealth materials, etc.).

Nanobots

Programmable nanoscale robots that are designed to attack certain types of targets (e.g. specific metals, internal organs, etc.). Tiny robots will be used both in medical applications as well as in future warfare.

Information Technology

"Information Technology" is another combined category consisting of applications that are used to process information. For example, the foresights see nanotechnology facilitating the development of smaller computers which can be more easily used on the battlefield.

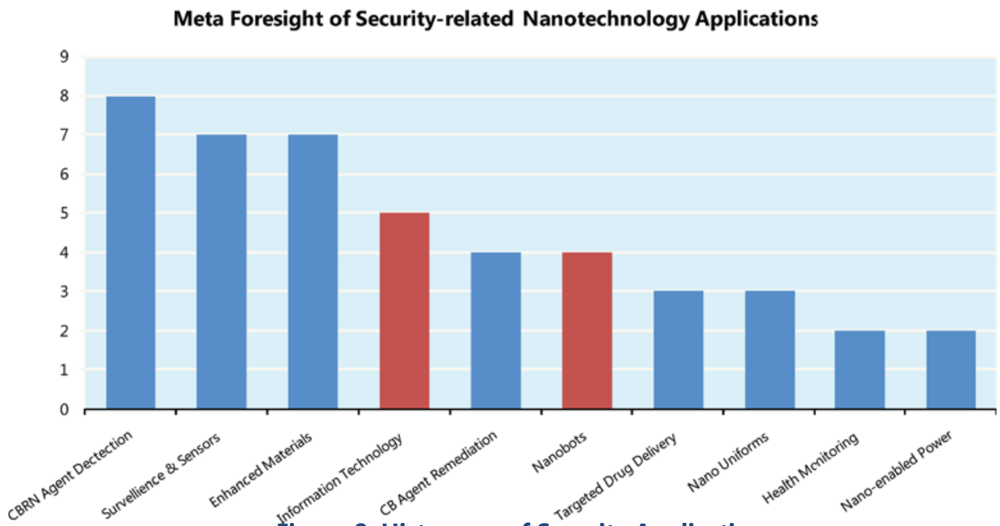


Figure 8: Histogram of Security Applications

With this list of security application, a histogram was developed depicting the number of foresights that mentioned each individual application (see figure 8).

Since the field of security technology received relatively little attention in the wider collection of foresights (see figure 1), the HCSS team decided to check for spillover effects from the top four fields (health & medicine, materials, environment, and energy). The applications in blue are those that have spillover effects.

While these applications are specifically developed for the security realm, there seems to be an apparent spillover effect from the top four technological areas on account of the fact that 78% of the security applications have clear and definite links with at least one of these areas (e.g., CB Agent Remediation – Environment).

Security Implications

The analysis of the drivers and parameters as well as the scenarios described above, show that nanotechnology's impact on national and international security is wide-ranging. Certain applications of nanotechnology, especially the ones highlighted above, are particularly important in shaping what the security environment will look like in the future and are instrumental in defining the various security implications of nanotechnology. The security implications of nanotechnology are aggregated on four different levels of analysis: field applications, national security strategies, strategic interactions among states, and international strategic environment.

Implications for Field Applications

Nanoweapons

Nanotechnology carries the potential not only to enhance weapons through refined and hardened materials (such as increasing the durability of missiles) but also to create nanotechnology-based or enhanced weapons of mass destruction (WMD). The scenarios described in the foresights that consider nanotechnology's WMD potentials ranges from realistic notions such as cell-targeting or targeted toxin-delivery to more improbable ones such as nanobots and the concept of "grey-goo", a scenario of swarming destructive nanobots, first envisioned in science-fiction writer Michael Crichton's Prey.

Human Augmentation

Nanotechnology, along with biotechnology, information technology, and cognitive science, collectively known as NBIC, provides the potential of addressing many human health issues as well as enhance the prospect of achieving human augmentation. Specific applications that involved the advancements in nanotechnology may include the miniaturization of sensors that can be more easily embedded into the human cognitive system that will allow soldiers to acquire greater situation awareness. Such advances can reshape how soldiers and human operations are understood on the battlefield.

Implications for National Security Strategies

Terrorism

Since nanotechnology has many potential applications in weapons, it also poses the risk of exploitation by terrorists. Terrorist concern is one of the more robust considerations in relation to nanotechnology foresight exercises that address security issues. In addition to the concerns of terrorist acquiring nano-based WMD, the foresight exercises also stress nanotechnology's potential as an enabling technology that can be used in conjunction with other technological advancements to redefine biological or chemical terrorism. A terrorist attack with nanotechnology-enabled biological agents may specifically target a certain racial group with similar genetic characteristics. Such an attack may not only cause social hysteria in the targeted group but also exacerbate any social cleavages based on racial lines.

Counter-Terrorism / Homeland Security

Nanotechnology can enhance the functionality of chemical and biological sensors that can be employed to prevent the occurrence of terrorist or conventional attacks using such agents. In addition to sensing, nanotechnology also provides the potential of remediation. Nanotechnology may lead to the development of successful counter-agents that can destroy offensive chemical or biological agents or contribute to cleaning up efforts after they have been used. This capacity can greatly upgrade and strengthen homeland security systems.

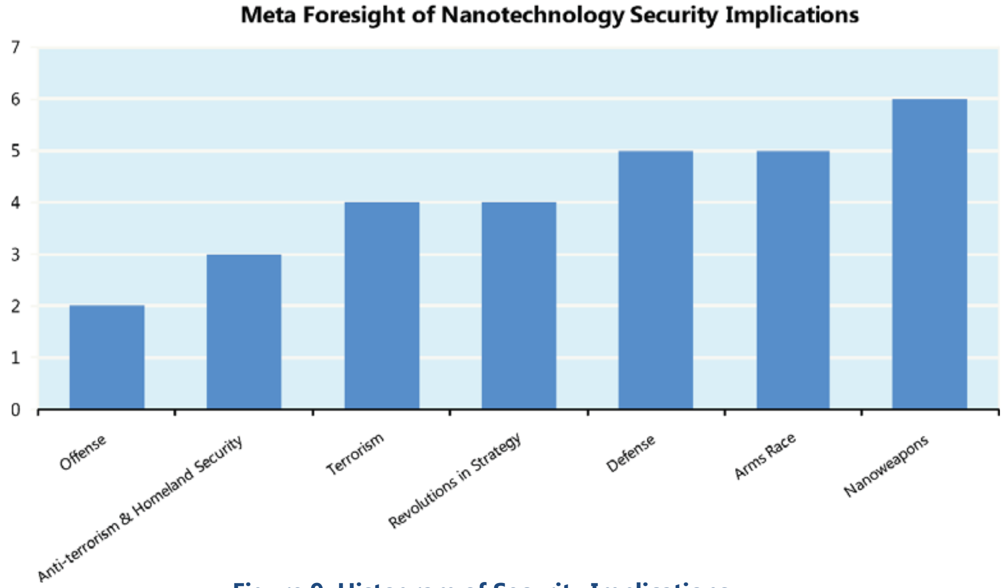


Figure 9: Histogram of Security Implications

Revolution in Military Strategy

Comprehensive sensing, health monitoring, advanced drug delivery, enhanced body armour, miniaturized and portable high-efficiency energy sources and much other technological potential is brought to bear by the advances in nanotechnology. These applications can change how militaries plan for and fight wars and, as a result, lead to a revolution in the tactics employed in military operations. The implementation of nanotechnology-related applications could lead to the creation of different chain-of-command structures in the military by redefining what soldiers are capable of doing in the field and how they communicate to their commanders.

Implications for Strategic Interactions among States

Arms Race

Nanotechnology can create a whole new class of weapons currently unregulated by any international regime or institution. As a result, it could lead to the next arms race between nations pursuing nanotechnology research. Some may see the potential edge provided by nanotechnology as a means to redefine the existing power balance. Foresights have referred to the nanotechnology ambition of states such as Russia and China as potential source of such rivalry in the future.

Issue of Access

In addition to the potential for arms race among more industrially advanced states, nanotechnology can also create a new technological divide among states, exacerbating struggles between the technological haves and the have-nots. States possessing the ability to pursue nanotechnology research or to achieve high degree of technological maturity can be further empowered in the international system like those who were early developers during the nuclear and information age. States without this capacity will be left further behind. This inequality of capability can become a new source of conflict especially between the developed and the developing world.

Conflict Prevention

In spite of the conflict potential of nanotechnology, it can also provide solutions to at least some international problems, for example the issue of energy scarcity. Nanotechnology's potential in energy creation and storage can possibly resolve some of the existing energy problems, such as the over-reliance on hydrocarbon as the main source of energy. Recent research in water filtration also suggests that nanotechnology has the potential to help resolve the issue of water scarcity.

Implications for International Strategic Environment

Stability

As described above, nanotechnology carries the dual potential of stabilising as well as destabilising the international system. While at present the exact effect cannot be fully assessed, nanotechnology is likely to be one of the defining technologies that determine what the international system looks like in the future: whether the world is stable or not depends on the extent to which countries can reap the benefits of the nanotechnology revolution.

Deterrence

Nanotechnology can potentially redefine the concept of deterrence. Rivalries between states in the nanotechnology era may not follow the traditional doctrine of deterrence that defines the nuclear age. Conflict and/or arms races between states may be less defined by the level of impact and destruction than by other means dictated by future developments in nanotechnology. In the future, deterrence may no longer be driven by the logic of mutual assured destruction but by other metrics of impact or social disruption that create different kinds of risk.

Conclusions

Governments will likely remain a key player in the development of nanotechnology based on their constant (long-term) commitment to nanotechnology foresight studies and the fact that foresights generally concur about both the likelihood and the importance of government participation.

Funding for nanotechnology related R&D and economic competition are seen as very important drivers of whether nanotechnology will have profit potential. Judging from current R&D budgets, actors appear willing to invest now in order to have a share of the estimated (and often cited) one trillion dollar nanotechnology market in 2015.

Funding also seems to drive application diversity. Increased funding for nanotechnology in different fields prompts the foresights to envision a future with a wide-range of nano-enabled products.

The nanotechnology future will not necessarily be a positive sum game: issues of access to nanotechnology and inequality are likely to arise. This in turn could have implications for stability – along the lines of the "haves" and "have nots"

The future remains fairly uncertain. Two of the scenarios provided show the future is unfolding in a manner favourable to nanotechnology, whereas two do not. Even if nanotechnology seems to be on the path to success, this is by no means guaranteed and will also depend on less easy predictable social, political and institutional constraints that might come in its way.

Nanotechnology's impact on national and international security is diverse. It has many field applications such as, a.o., nanobots, nanoweapons and human augmentation devices. These could have wide ranging implications for the nature of states' interactions both in peace- and in wartime.

Appendix A Technological Fields

Based on research and application direction HCSS identified eight important technological fields within the nanotechnology realm. The chosen fields and some key applications are detailed in the following list.

Health & Medicine

This field includes the research and applications aimed at advancing medical science and improving human health.

One application of this field is targeted drug delivery. Through precision discrimination on the nanoscale, this technology delivers the necessary drugs to only the points that require treatment. The foresights suggest that targeted drug delivery could be employed as a more effective means of administering antibiotics and chemotherapy.

Materials

This field involves improving material properties (e.g. strength, flexibility, hardness and weight) through the use of nanotechnology.

Nano-enabled anti-ballistic material would fall into this field. The physical properties of nano-materials allow more material to be packed into the same amount of space than the current designs. This affords nano-enabled anti-ballistic material a higher impact resistance and the ability to stop larger projectiles.

Environmental

This field encompasses the research and applications that address environmental issues (such as carbon dioxide reduction).

One application of this field is waste remediation. The chemical properties of nanoparticles allow them to bind with a wide variety of materials that had previously posed disposal problems (e.g. organic contaminates, chemical agents and heavy metals) and neutralize them.

Energy

This field involves the nanotechnology endeavours that address the issues of energy sources, and power.

Nano-enabled solar cells offer an example from the energy field. The inherent material properties of nanotechnology not only increase the energy conversion rate of this technology but also make it smaller, lighter, and more flexible, which affords users portability and even wearability capabilities.

Electronics

This field includes applications and research that deal with electronics. Please note that this does not include computers. These are included in the "Information and Communications Technology" field instead of this one.

An example of the electronics field involves the integrated circuit chip design. Nanotechnology affords manufacturing and material advantages which will allow the integrated circuit chip to advance greatly beyond it current capabilities.

Information and Communications Technology (ICT)

This field deals with computers, information processing systems, and communications technology.

High performance memory storage is a nano-enabled application within the ICT field. It is made possible through the same reasons as integrated circuit chip design.

Manufacturing

This field focuses on nanotechnology and product assembly, which can range from nano-manufacturing, bottom-up synthesis, to nano-enabled improvements to in large-scale manufacturing processes.

Molecular manufacturing, engineering systems at the molecular scale, is an example of an application in this field.

Security

This field involves those nanotechnology endeavours that are geared towards a specific role within the security realm.

Chemical, biological, radiological, and nuclear (CBRN) agent detection offers an example of nanotechnology in this field. Nanoporous materials enhance the detection process because they have an extreme sensitivity to environmental changes and a disproportionately high surface area, which is useful for catching and scanning more molecules.

Appendix B - Parameters

A number of parameters were identified within the nanotechnology realm. HCSS analysts coded these insights into nine individual parameters, which are described in a subsequent list. Additionally, values were given to these parameters with the higher numbers representing the situations where nanotechnology has a better chance to thrive. A description of the identified parameters and the codebook are provided below.

Impact of Nanotechnology

This parameter analyses how the foresights perceive the impact of nanotechnology on a scale from evolutionary to revolutionary. The foresight exercises that see nanotechnology merely as an enabling technology are coded as a one. Those that consider nanotechnology to drastically change certain sectors are scored with a two, and the foresights that view nanotechnology as having a significant impact on the whole of society are given code three.

Operationalisation: 1 = technologically evolutionary; 2 = sectorally revolutionary; 3 = socially revolutionary

This parameter is of particular importance because it partially sets the tone for the future. If the impact parameter is perceived to be low, then several of the other parameters (e.g. economic potential) might also be low.

Level of Interest

This parameter analyses the level of interest that society as a whole will have for nanotechnology. Higher levels of interest generally correspond with a greater amount of envisioned nanotechnology benefits. The foresights are coded thusly from low to high in terms of the level of interest that nanotechnology will sustain.

Operationalisation: 1 = low; 2 = medium; 3 = high

The level of interest parameter is important because it offers a means of accounting for a thriving nanotechnology future when public tolerance for nanotechnology is quite low. When the public is risk averse, they would tend not to favour nanotechnology development, but if the interest level in nanotechnology is high, then the public might be willing to put their concerns aside.

Public Tolerance

This parameter analyses the public's willingness to accept the risks associated with nanotechnology. The foresights that emphasise nanotechnology's social and technical concerns suggest a higher level of risk associated with the applications of nanotechnology. Public tolerance of nanotechnology is coded on a scale from averse to tolerant.

Operationalisation: 1 = risk averse; 2 = neutral; 3 = risk tolerant

This parameter is important because it offers a means of capturing public opinion, which the foresights consider to be a major factor in determining the success of nanotechnology.

Dominant Actor

This parameter analyses the sector that plays the main role in directing or leading the research of nanotechnology as suggested by the foresight. Foresights that see the public sector as the dominant actor in nanotechnology research direction are coded as 1. Foresights that see the private sector as the dominant actor are coded as 3.

Operationalisation: 1 = public; 2 = mixed; 3 = private

Nature of Government Participation

This parameter analyses the kind of role that government plays in terms in the development of nanotechnology. Foresights that see the government mandating clear directions for nanotechnology research are coded as 1. Those that see the government devising some kind of national nanotechnology strategy are coded as 2, and the foresights that see the government providing only some general recommendations are coded as 3.

Operationalisation: 1 = mandates; 2 = strategies; 3 = recommendations

Source of Regulation

This parameter analyses how the foresights see nanotechnology being regulated in the future. Foresights that view state and government-based legislations as the dominate form of regulation are coded as 1, whereas those that view the market and enterprise as the main regulatory mechanism are given a score of 3. The foresights fall between these two poles are give the coded as 2.

Operationalisation: 1 = state-based; 2 = mixture; 3 = market-determined

The institutional parameters (4-6) are important because they offer insights into the nanotechnology innovation process. Together, these three parameters show the degree of government intervention in the market and innovation process, which has implications for several other parameters (e.g. economic potential, impact, market diversity, etc.)

Economic Potential

This parameter analyses the level of economic potential the foresights attribute to the future of nanotechnology. The parameter is operationalised from fruitless to profitable in terms of the foresight's perspective on nanotechnology's potential for profit and commercial success.

Operationalisation: 1 = fruitless; 2 = moderate; 3 = profitable

The economic potential factor is important because it notes whether or not there is an incentive to invest in nanotechnology development.

Market Diversity

This parameter analyses the level of market diversity envisioned by the foresights. The parameter is operationalised from niche to highly diverse markets.

Operationalisation: 1 = niche; 2 = moderately diverse; 3 = highly diverse

The market diversity parameter is important because it informs several of the other parameters (impact, economic potential, and level of interest). For instance, if there are only niche markets, then the impact of nanotechnology is unlikely to be socially revolutionary.

Application Diversity

This parameter analyses the level of emphasis that each foresight places on certain future applications of nanotechnology. This is an aggregate parameter derived from the conceptual use of nanotechnology. Foresights that emphasise a nanotechnology application in a single field will be coded as 1; foresights that emphasise a set of wide-ranging applications in multiple fields will be coded as 3.

Operationalisation: 1 = niche; 2 = moderately diverse; 3 = highly diverse

The application diversity parameter is important because it notes the breadth of the commercialisation process.

Appendix C drivers

HCSS identified nine drivers from the foresights. A description of these drivers is provided below.

"Nano Experience"

Nano experience denotes the degree to which prior experiences with nanotechnology shape the present choices. Foresights often discuss this driver under the context of a catastrophic or catalytic event or set of events that can help determine the degree and the direction to which nanotechnology will develop. Foresights considering nano experience as a driver often include in their discussion or analysis potential nanotechnology disasters or breakthroughs as part of the driving force for nanotechnology development.

Nano experience is an important driver because the best estimator of what a society feels today is what it felt yesterday. If a society had a bad nano experience, then it will most likely view nanotechnology in a bad light today or in the future.

Social Concerns

Social concern denotes the concerns that the public may have in regard to nanotechnology's impact on society. Foresights that discuss this driver suggest that nanotechnology carry the potential social risk in terms of privacy, disparity (technical divide between), and inequality (the level of accessibility of the technology). Foresights considering social concern as a driver often include the need for a review on nanotechnology's social impact as well as plans for the social problems that nanotechnology may bring as part of their policy recommendations. Social concerns are also an important driver because they factor into the public tolerance level. If nanotechnology is thought to produce adverse social consequences (e.g. inequality), the public's risk tolerance might decrease.

Economic Competition

Economic competition denotes the competition that the market actors face in the field of nanotechnology research and development. Foresights that discuss this driver suggest that the level of competition experienced in the nanotechnology R&D market will help determine the degree to which nanotechnology will develop. Foresights considering economic competition as a driver often include reforms or adjustments of business climate, entrepreneurship, or market structure as part of their policy recommendations. Economic competition is an important driver because it sparks interest in nanotechnology and helps to promote advances in nanotechnology. Those actors (e.g. states, individuals, corporations, etc.) that remain on the cutting edge of nanotechnology will accrue the most benefits. If the business climate is competitive, this means that actors will have to put more effort into remaining competitive (e.g. more investment).

Technical Concerns

Technical concern denotes the concerns that the public may have in regard to nanotechnology's toxicity or other health or environmental impact. Foresights that discuss this driver suggest that nanotechnology carry potential technical risks in terms of its effect on human and environmental health, and level at which the public is concerned about these kinds of technical risk will help determine the degree to which nanotechnology will develop. Foresights considering technical concern as a driver often suggest the need for careful reviews regarding nanotechnology's impact on health and environment as part of their policy recommendations.

Technical concerns are an important driver because, like social concerns, they play into the public tolerance level. Technical concerns, however, address entirely different issues than social concerns, which is why the two have been separated.

Human Capacity

Human capacity denotes the suitability of the workforce for the development of nanotechnology. Foresights that discuss this driver suggest that the workers' and researchers' ability and knowledge will help determine the degree to which nanotechnology will develop. Foresights considering human capacity as a driver often include the establishment of college degree or other educational programs to foster the workforce capable of future nanotechnology research as part of their policy recommendations. Human capacity is an important driver because the capabilities of the workforce are either an enabling or limiting factor in the nanotechnology commercialisation process.

Problem Solving Potential

Problem-solving potential denotes the potential that nanotechnology has in solving some of the today's pressing problems, such as energy, health, or environmental issues. Foresights that discuss this driver suggest that the potential of nanotechnology in solving large-scale human issues such as fuel scarcity, cancer, or climate change will help determine the degree to which nanotechnology will develop. Foresights considering problem-solving potential as a driver often indicate such a potential as a reason of why nanotechnology research is needed and important for the future in their analysis. This is an important driver on account of the fact that it serves to change the level of interest parameter, which can somewhat offset values in the public tolerance parameter.

Commercialisation

Commercialisation denotes the degree to which nanotechnology is able to be transferred from the laboratories to the market. Foresights that discuss this driver suggest that the ability of nanotechnology to move from the research to production will help determine the degree to which nanotechnology will develop. Foresights considering commercialisation as a driver often include profitability, business incentives, and research-production process as part of their analysis and policy recommendations. Commercialisation is a key driver because it deals with the moving products from the research and design phase to the market. As such, this driver influences impact, economic potential, and application diversity.

Research & Scientific Capacity

Research/Scientific Capacity denotes the suitability or the condition of research and scientific community for the development of nanotechnology. Foresights that discuss this driver suggest that the kind and the condition of research and scientific infrastructure will help determine the degree to which nanotechnology will develop. Foresights considering research/scientific capacity as a driver often include the reform of research process as well as the establishment of research infrastructure capable of future nanotechnology research as part of their policy recommendations. Research and scientific capacity is a main driver because it directly affects commercialisation potential.

Funding & Investment

Funding & Investment denote the level of funding that nanotechnology research and development receives. Foresights that discuss this driver suggest that the level of funding and investment available in the nanotechnology R&D will help determine the level to which nanotechnology will develop. Foresights considering funding and investment as a driver often include the need for public funding and private sector investments in current nanotechnology research as part of its analysis and policy recommendation. Funding & Investment is a main driver because it influences the extent of the research efforts.

Further Reading

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Figure 1

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Figure 3

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Figure 4-9

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