Nanotechnology and Sustainability:
A Critical Review of Current Trends and Future Developments

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Master of Science Thesis
Stockholm 2009

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Keywords: nanoscience, nanotechnology, sustainability

Master of Science Thesis
Stockholm, Sweden 2009

Presented at: Division of Industrial Ecology
Royal Institute of Technology

TRITA-IM 2009:14
ISSN 1402-7615

Industrial Ecology,
Royal Institute of Technology
www.ima.kth.se

Abstract

This report considers both contributions and adverse consequences, uncertainties, and unknown relationships that are potentially involved in the advances of techno-economic and humanistic interests towards the advances in Nanosciences and Nanotechnologies (N&N). Because of the distinctive physical and chemical properties of materials at nanoscales, which have not been understood deeply yet, besides the huge potentials to benefit many areas of research and application, it is recognized that application of N&N may raise new ecological, health and safety, socio-economic, and regulatory challenges that will require scientific, techno-economic, and societal considerations. A comprehensive literature survey of peer reviewed journals, books, and other authoritative sources indicate that there have been very few studies on these fundamental aspects and the research investments are mainly sponsored for market purposes, rather than for pure scientific structure-function discoveries or sustainability attitudes. The overarching issue of importance in this study is to consider the high level of uncertainties and lack of knowledge in N&N, and the great potential threats and impacts of engineered nanoproducts that can be either in form of known-unknowns or even unknown-unknowns. Moreover, measures of improvement to govern N&N developments to become sustainable, including public communication, call for pure and high quality non-prescribed research on unknown characteristics of N&N, health and environmental friendliness based on a life cycle approach, and the industrial ecology approach, together with implementation of the related results in practice have been suggested.

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1. Introduction

Nanotechnology is considered to be one of the most prominent emerging technologies of the 21st century and has been described with several main characteristics such as transformative technology, enabling technology and the technological revolution. According to Encyclopædia Britannica (2009), nanotechnology is the manipulation and manufacture of materials and devices at a scale of less than 100 nanometers (one nanometer is equal to one millionth of a millimeter) or small groups of atoms. Materials built at this scale often exhibit distinctive physical and chemical properties due to quantum mechanical effects. Although usable devices at this small scale may be years away, nanotechnology as multi-disciplinary field working at nanoscales and utilizing new instrumentation is recently available. Furthermore, a huge flow of money is being spent for technical research and academic disciplines on Nanosciences and Nanotechnologies (N&N).

The prefix 'nano' is derived from the Greek word for dwarf. A human hair is approximately 80,000 nm wide, and a red blood cell approximately is approximately 7000 nm wide (The Royal Society & The Royal Academy of Engineering, 2004, p. 5). The basic concept of nanotechnologies was firstly recommended by the physicist Richard Feynman in 1959, in his lecture "There's plenty of room at the bottom" (Feynman, 1959). He explored the possibility of manipulating materials at the scale of individual atoms and molecules, imagining the whole of the Encyclopædia Britannica written on the head of a pin. The exact term of ''nanotechnology'' was first introduced by a Japanese engineer, Norio Taniguchi. The term originally implied a new technology that went beyond controlling materials and engineering on the micrometer scale, which had dominated the twentieth century (Uskokovic, 2007). According to The Royal Society & The Royal Academy of Engineering (2004) **"Nanosciences** are the study of phenomena and manipulation of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale." and "**Nanotechnologies** are the design, characterization, production and application of structures, devices and systems by controlling shape and size at nanometer scale."

N&N have reached substantial growth, development, and commercialization during the recent years and a wide range of advances in a variety of fields including IT, computer efficiency, human organ restoration, environmental, water, and energy technologies, specific materials from direct assembly of atoms and molecules, etc. are being facilitated by the developments of N&N. According to Arnall (2003), 2002 was the year in which US corporate funding matched state funds and could be considered as a milestone in development research on nanotechnology. This is because transnational companies realized that nanotechnology was likely to disrupt their current products and processes, and because the investment communities have noticed that nanotechnology is the 'next big thing'. All of these show the importance and high rates of developments in the fields of N&N.

Thanks to the extraordinary abilities at nano dimensions, N&N have the potential for great contributions towards sustainability challenges in most of the branches including resource efficiency, energy technologies, environmental monitoring and remediation, chemistry, water technologies, health technologies, and medical applications. There are numerous research result documents, papers, and other types of literature on N&N contributions to the challenges and needs of the current world.

However, despite the fact that most of the new technologies, including nanotechnologies, are applied to solve specific problems, it is crucial to consider their potential risks and adverse consequences due to their unknown or unpredictable effects on the sensitive systemic parameters of the environment, economy, or society. There have been just little research and investigation on the potential risks and side effects of N&N and this together with the increasing rates of commercialization of nanoproducts can act as significant threats towards reaching the world's sustainability goals. Arnall (2003) states that in 2002, of the US$ 710 million spent by the US government on nanotechnologies, only US$ 500,000 – equal to 0.07% - was spent on environmental impact assessment and relatively nothing was spent on social impacts. Therefore, both sides of effects of N&N developments – both the potential positive effects and the negative consequences - must be considered and investigated simultaneously. Furthermore, the available scattered amount of facts on the both sides should be collected, reviewed, classified, and analyzed with a systematic approach. Out of this comprehensive review, improvement suggestions to govern N&N towards sustainability perspectives should also be noticed and analyzed.

2. Aim and Objectives

This study aims to survey both current trends and possible future advancements of N&N along with reviewing articles on the related contributions and adverse impacts, with a critical approach towards sustainability perspectives. This also encompasses recommendations to make nanotechnology development trends sustainable. In particular, a well structured literature review of nanotechnology developments in all related fields, including those having concerns about current trends and future developments is conducted. Finally, the contributions, challenges, concerns, and practical measures towards a sustainable N&N development world are identified and highlighted.

It is worth noticing that the sustainability discourse requires consideration of techno-economic, ecological, and social sustainability aspects. While techno-economic aspects are well integrated in conventional economic evaluations and feasibility studies such as cost-benefit analysis, ecological/health/environmental and social risks and impacts are traditionally so-called externalities and have not been taken into consideration as they deserve. Therefore this study focuses on social and ecological sustainability issues, with special focus on ecological sustainability aspects.

3. Methodology

The study was carried out by the aid of literature studies, books, authoritaty documents and records. The literature review focused on peer reviewed papers and reports from other authoritative data sources. Documents and records were taken from different laboratories, universities, research institutes, and organizations working on the related subjects. Data related to the subject of the study in the fields of N&N, including their contributions, concerns, and governance towards sustainability goals were reviewed and an analytical, critical, and suggestive review of the gathered data together with the author's own analyses and recommendations, were classified and presented in the report.

4. Basic Concepts in Nanosciences and Nanotechnologies (N&N)

4.1. What are Nanosciences and Nanotechnologies

A combination of the current and previously mentioned definitions of N&N that will used in the sequel could be as follows: Nanosciences can be defined as the study of phenomena and the manipulation of physical systems that produce significant information (i.e., ‘‘readable’’ differences) on a spatial scale known as ‘‘nano’’ (10^{-9} m or 1 nm), with boundaries smaller than 100 nm in length at least in one dimension. Therefore, nanotechnologies focus on the design, characterization, production, and application of nanoscale systems and components (Uskokovic, 2007).

It is now useful to have some information about the different characterization of materials at nanoscales and several approaches utilized in the field of nanotechnologies.

4.2. When Macro and Micro Become Nano

Decreasing the grain size of a material to nano limits results in the appearance of either new or changed properties of the material due to:

- inherent crystalline grains approaching the size of the characteristic physical lengths of the relevant properties;
- an increase in the proportion of interface defects and their impact on dependent properties; and
- the appearance of new structural properties that characterize the grain boundaries of the material

By reducing sizes down to certain limits, the cohesive influences of gravitational forces give right to Morse function-shaped electromagnetic forces and the quantum effects which come from electronic properties. When the lower size limit of nanomaterial grains approaches that of regular clusters, quantum effects overcome surface effects and become the dominant factor in defining measured properties (Uskokovic, 2007).

Thus size effects in nanomaterials are of great complexity and problematic too. It seems to be likely that, despite a great body of information, the understanding of the nature of size effects in nano scales is not so deep and the possibility of prediction in this field is limited. Furthermore, there are some complications in the preparation and characterization of representative samples. The knowledge of the size effect nature, in the context of fundamental significance and still incomplete data, requires intense research and study in order to highlight the best strategies for future technologies (Andrievski & Glezer, 2001). Thus there is a great potential risk of unknown unknowns in the development and implementation of nano materials and the potential future impacts or side effects to the environment and the biota are really difficult to discover, and even in some cases impossible to guess.

4.3. Approaches to Design and Technology in N&N

4.3.1. Bottom-up and Top-down Approaches

According to The Royal Society & The Royal Academy of Engineering (2004, pp. 26-28), there are mainly two approaches for manufacturing nanomaterials: ‘bottom-up’, and ‘top-down’ approaches. In recent years the limits of each approach, in terms of feature size and quality that can be achieved, have started to converge. Bottom-up manufacturing means the building of structures, atom-by-atom or molecule-by-molecule while top-down manufacturing involves starting with a larger piece of material and processing it to get a nanostructure from it by removing material (as, for example, in circuits on microchips).

According to the definition of nanotechnologies mentioned before, any technology that manipulates material on a nanoscale, including ‘‘top-down’’ or “bottom-up” techniques, can be referred to as nanotechnology.

4.3.2. Hard-tech and Soft-tech Approaches

Uskokovic (2007) categorizes two types of attitudes which could be found in the bottom-up approach: the hard-tech approach and the soft-tech approach. In the hard-tech approach, atom-by-atom or molecule-by-molecule manipulations are induced with the use of massive and complex apparati in order to organize relatively simple building blocks into applicable nanostructural outcomes. While the ideal of ‘‘everything is possible’’ dominates the hard-tech approach, the uncertainties and problems are much more in this approach. The idea of Richard Smalley, Nobel Laureate in chemistry and an advocate of soft-tech approach, about hard-tech approach might be interesting:

> *”Much like you can’t make a boy and a girl fall in love with each other simply by pushing them together, you cannot make precise chemistry occur as desired between two molecular objects with simple mechanical motion along a few degrees of freedom in the assembler-fixed frame of reference. Chemistry, like love, is more subtle than that. You need to guide the reactants down a particular reaction coordinate, and this coordinate treads through a many-dimensional hyperspace.”* (Baum, 2003)

In the soft-tech approach, the design of complex building blocks is carried out via self-assembly by performing manipulations on a macroscopic scale. This approach uses relatively inexpensive and easily accessible equipment that might naturally result in decentralization of power and sustainable development of practical knowledge (Uskokovic, 2007).

4.3.3. Trial-and-error Approach

The standard approach in nanotechnology is to come up with new chemical structures through trial and error, by letting constituent parts react with one another as they do in nature and then observing whether the result is useful. With current knowledge in N&N, prediction of the outcomes of experimental settings that aim to produce new nanostructures and morphologies is extremely difficult, or practically impossible. Thus the best results in today’s practical nanoscience come from trial-and-error approaches. There is considerable evidence that slight condition changes in nanoparticle synthesis experiments will produce significant differences in the end results (Princeton University, 2006).

A very important issue to consider is to distinguish the domains of what is known and possible on one side, and unknowable and impossible to know or obtain on the other side. This - discerning unknowable and unattainable from generally impossible to achieve - is never easy.

Some limits, such as production and technical limits could be surpassed. Other limits, like Heisenberg's uncertainty principle or the laws of thermodynamics, are impossible to surpass and will never change. New technologies have never perfectly solved certain problems they aim to fix, but they do expand the potential options for both risks and benefits, keeping them in creative balance, and thus encouraging an eternal search for innovation and advancement through problem solving. N&N can not be excluded from this fact.

5. Nanosciences and Nanotechnologies Contributions Towards Sustainability

Materials expose extraordinary abilities at nano dimensions and this enables N&N to contribute in some of the most challenging areas of sustainability. Although N&N have the ability to contribute in these challenging areas, including resource efficiency and water, energy and environmental technologies, they carry potential risks because of their unknown or unpredictable effects on the sensitive systemic parameters of the environment, economy, or society. As a rule of thumb, the more prosperous a technology appears the more unpredictable consequences and potential risks it carries. Therefore, both sides of the emerging nanotechnologies - their potential positive effects and negative consequences - must be considered and investigated simultaneously. However, statistics (Arnall, 2003) show the lack of investigations on nanotechnologies in a basket of two parallel insights from the sustainability point of view. In this report, both insights will be presented with a critical approach, including improvement suggestions and corrective measures. In this chapter, the potential advantages of nanotechnologies are being discussed. The potential side effects and adverse consequences of nanotechnologies will be discussed in the next chapter.

5.1. Resource Efficiency

Sustainable development may in a simplified way be described as providing the basis for economic growth while ensuring protection of environmental and social values. N&N can contribute to saving resources through improvements in efficiency of renewable energy sources and energy storage devices, development of less energy consuming components, reducing consumption of materials, and making the possibility of substituting alternative, more abundant materials for those that have limited availability. An increase of resource efficiency is one of the most important possibilities that N&N provide for a future technology world. Nanotechnologies are regarded as highly promising in terms of sustainability, in particular to permit much higher resource productivity, lower emissions and de- or immaterialization of economic processes. Many scientists and engineers believe that nanotechnology manufacturing promises less material and energy consumption and less waste and pollution disposal in the life cycle of industrial products. It is also expected to result in new technological approaches that reduce the environmental footprints of existing technologies in industrialized countries or allow developing countries to address some of their most critical needs (Fleischer & Grunwald, 2008).

Nanotechnologies in their ideal bottom-up approach enable manufacturers to produce devices from a minimum of raw material resources and thus are considered as a great hope for resource efficient production methods. This does not mean that current top-down approaches are not efficient. As summarized in table 1 (Gleich, et al., 2007, p. 902), nanoparticles are characterized by certain properties enabling the manufacture of nanostructures that are much more efficient than common macro- and micro-dimensional production technologies. Nanomaterials can also work with optimum resource consumption and energy demand rates which results in less material and energy use in the consumption phase of the life cycle.

However, although there is a broad consensus that adequate and targeted innovation is a key factor in getting closer to sustainable development, but what ‘‘adequate’’ actually means is ambiguous. It is necessary to understand that the meaning of ‘‘adequate’’ cannot be clarified by only using technical parameters. The real impacts of a new set of emerging technologies like nanotechnologies on sustainability arena is a product of both the technical parameters and the social environment of the set of technologies, including their social consequences, the usage patterns, secondary effects, etc. Thus technical innovations are necessary but not sufficient. Therefore, an extended notion of innovation including technical, social, and institutional aspects must be applied (Fleischer & Grunwald, 2008).

Table 1 - Characterization of nanostructures regarding some potential opportunities for resource efficiency. Source: Gleich, et al., 2007, p. 902.

Nano-characteristic	**Positive resource efficiency impacts**
Small particle size and particle mobility	Selective use for resource- and eco-efficient technology
Precision, particle size/layer size, purity	Selective use for resource- and eco-efficient technology
New chemical effects, modified behavior	Utilization of modified behavior for resource and environmentally efficient technologies, e.g., use of catalytic effects for more efficient chemical processes or in the environment
New physical effects, modified optical, electrical, and magnetic behavior	Selective utilization of effects and modified properties for resource and environmentally efficient technologies, e.g. quantum effects
Self-organization, Self-replication	Selective use of biomimetic self-organization for resource /eco-efficient and consistent technologies

5.2. Technical Contributions

Nanotechnologies are important factors of innovation in the chemical industry and other materials-based industries that environmental concerns will influence future product development. Carbon nanotubes have many potential applications, such as high-strength composites, energy storage and energy conversion devices, sensors, hydrogen storage facilities, nanoscale semiconductors, probes, and interconnects. Very high specific surface areas (up to $3500m^2/g$) are attainable through using nano-structured Metal Organic Frameworks. The production costs are still too high but the development of innovative processes can be expected to reduce them. A decrease in the cost of single-walled nanotubes from the present $ 1000/kg to less than $ 50/kg would make their widespread use economically feasible. Advanced lithium energy storage systems can increase the power output of rechargeable lithium-ion batteries from the present 200 Wh/kg to 300 Wh/kg by using nanostructured electrode materials. Electron production per electrode atom has been increased from 0.6 to 2 with nanostructured lithium cobalt oxide (Rickerby & Morrison, 2007). All of the mentioned examples could be regarded as technical contributions of N&N in several areas of research and development.

5.3. Nanotechnologies as Enabling Technology

One important general characteristic of nanotechnologies that is necessary to mention before going into details is the role of nanotechnologies as a so called enabling technology. There are of course pure nanotechnology products like nanoparticles for medical or cleantech applications. But in most of the cases, a nanotechnology product is an important and decisive ingredient of a more elaborated and usually macro product. In these cases, the nano content might not be tangible or recognized easily. These kinds of products are increasingly used in a number of fields like energy technology, information and communication technology, military technology, and biotechnology (Fleischer & Grunwald, 2008).

To add to the complexity, some of the technology fields mentioned are integrated into meta-technologies. A metatechnology is a technology which not only provides direct capabilities, but one that also affects other technologies to dramatically improve system performance (Molecular Manufacturing Shortcut Group, 1993).

Nanotechnologies and especially molecular nanotechnologies are impending metatechnologies which should enable vast transformations in the coming decades. All of these fields are growingly intertwined and interacting with society. For many nano-enabled technologies it therefore might become more and more problematic to attribute their sustainability effects to nanotechnologies. Thus it is a subject that systems engineers should begin studying.

As an important rule of thumb, science and technology, and nanotechnologies in particular, cannot make miracles that will solve all sustainability problems. N&N may act as critical enabling components of sustainable development if and only if they are used rationally and when the economic and social context of their application is considered (Fleischer & Grunwald, 2008).

5.4. Energy Technologies

In recent years, climate impact and sustainable energy have come to the top of the world's political and scientific agenda. Since both developed and emerging economies strive for growth, worldwide energy demand is increasing. According to some anticipations, the total world energy consumption is expected to increase by about 2.0 % annually until 2030 (International Energy Agency, 2006). On the other hand, more than 2 billion people in developing countries still do not have access to reliable sources of energy. Since the world energy system will continue to be dominated by fossil fuels, this has immediate consequences for the greenhouse gas emissions and consequently global warming. This is especially true for the global CO_2 emissions that are expected to increase more rapidly than energy consumption because the highest growth rates can be found in regions that are highly dependent on fossil energy resources. Political initiatives to address these challenges are usually focusing on three themes:

- governing towards higher energy efficiencies,
- increasing the share of renewable energy sources and capturing carbon from energy, and
- catalytic and other types of conversion of emissions.

For a number of the technologies proposed above, nanotechnologies have the potential to play an important role (Fleischer & Grunwald, 2008). The following two subparts present two of the most important potential contributions of N&N in the field of sustainable energy production.

5.4.1. Direct Conversion of Sunlight into Electric Power Using Solar Cells

One of the most interesting and most flexible renewable energy technologies is the direct conversion of sunlight into electric power using solar cells. Existing photovoltaic technologies have low energy conversion efficiencies and are too costly. Nano-structured photovoltaic devices such as those using quantum dots have considerable potential for cost reduction. They are able to collect light from a broader range of wavelengths of the sun's spectrum than conventional cells. Hetero-structured absorber layers may further increase the cell efficiency or permit the use of lower quality materials for the cells. Nano-structured materials may feature stronger light absorption than their bulk counterparts. Semiconductor quantum dots (QDs) are of general interest due to momentum delocalization and relaxation of selection rules resulting in enhanced cross-sections compared to the bulk counterpart. On the basis of impact ionization, single photon generation of multiple excitons has been demonstrated in PbSe, CdSe and PbS QDs, which is raising the theoretical efficiency limit impressively (Zäch, et al., 2007).

Nanoporous silicon, with its anti-reflection and light trapping properties, has advantages as a proper material for solar cells with the reduced thickness of the active layer due to the lower diffusion length for efficient charge collection, and a higher achievable voltage. Its porous structure besides the increased light absorption results in higher internal quantum efficiency (IQE). Also organic solar cells have been recently developed using TiO_2 nanoparticles coated with an organic dye to convert light into energy by a process that is similar to photosynthesis. Absorption of photons by the TiO_2 causes electrons to escape into the conduction band and the particles to diffuse towards the positive electrode; iodine ions in the electrolyte collect electrons at the negative electrode and thus generating a current to flow. Although the conversion efficiency is only around 10 %, this type of cell can be manufactured from cheap and low purity materials using simple methods (Rickerby & Morrison, 2007).

5.4.2. Direct Conversion of a Fuel into Electricity

Another important future energy option is hydrogen or methanol, but it is still facing some critical technological challenges. Among those are ways to produce and store hydrogen or to convert it to electricity. Fuel cells (FC) are electrochemical devices that convert a fuel such as hydrogen or methanol directly to electricity through an electro-catalytic process rather than by combustion, thus potentially yielding much higher energy conversion efficiencies than in conventional combustion engines. With hydrogen as a fuel, the fuel cell is an extremely clean energy converter (but remember that an overall cleanness, based on Life Cycle Analysis (LCA), depends on how hydrogen is produced). It is obvious that a viable strategy to produce hydrogen depends on technologies that use renewable resources. One of them is the direct catalytic conversion of water into oxygen and hydrogen by using a nano-structured semiconductor catalyst or nanoscale additives (Fleischer & Grunwald, 2008).

At the heart of a fuel cell are the electrodes, on which the actual electro-catalytic conversions occur. The requirements for the electrodes are a high surface/volume (S/V) ratio and durable materials that do not degenerate by the electrochemical process and that are not poisoned by fuel impurities, and furthermore short and low resistance charge transport distances from the catalyst surface to the external circuit. In order to meet these requirements, conventional FC electrodes are composed of finely dispersed electro-catalyst particles on a high surface area carbon support. The structure of these electrodes is very complex, making it difficult to establish a detailed and systematically investigated structure – performance relationship. Planar model electro-catalysts, which are fabricated and characterized with the aid of nanotechnology, allow one to control the size, shape, separation and chemistry of the catalyst particles and to systematically investigate the influence of these parameters on the electrocatalytic reactions (Debe, et al., 2006).

The second key component of a fuel cell is the electrolyte which for polymer electrolyte fuel cells typically consists of a Nafion membrane. Nafion is a type of synthetic polymers with ionic properties and the greatest interest in it in recent years comes from its consideration as a proton conducting membrane in proton exchange membrane fuel cells (Mauritz & Moore, 2004). One of the limitations of current Nafion-based membranes is the loss of proton conductivity at operation temperatures above 100 ^{o}C, with a concurrent decrease of the cell performance. It is yet desirable to operate the cell at increased temperatures. Water uptake, conductivity and electrochemical performance of Nafion membranes at high temperatures have successfully been improved by inclusion of nanometer-sized inorganic fillers (e.g. TiO_2). In a parallel line of development, nanomaterials such as titania nanotubes have recently been found to show interesting proton conducting properties at temperatures exceeding 100 ^{o}C and are therefore expected to contribute towards improved membranes (Zäch, et al., 2007).

Nanotechnologies can also support technological approaches to harness biogenic hydrogen. For building a hydrogen energy infrastructure and especially for applications in transportation, new lightweight, efficient and safe hydrogen storage systems are required. Materials under investigation for hydrogen storage are nanostructured carbon-based materials, such as carbon nanotubes, and complex metal hydrides like alanates. Their properties can be further enhanced by adding nanoscale structures. Other energy technology options include high efficiency devices for lighting or appliances, new materials for low loss power transmission lines or high strength lightweight materials for transportation, construction or electric power applications (Fleischer & Grunwald, 2008).

5.5. Environmental Monitoring

The ability to detect and quantify chemicals and toxic agents is an important step towards distinguishing environmental problems and taking remedial actions and nanotechnologies can help providing improved systems for environmental monitoring. Currently used monitoring systems for air pollution consist of huge stations situated in certain areas at geographically separated locations that fail to meet the need for monitoring hot-spot pollution peaks.

Solid state gas sensors based on nanocrystalline metal oxide thin films are able to provide faster response with real-time analysis capability, higher spatial resolution, simplified operation and lower running costs in comparison to conventional methods such as infra-red spectrometry. Their sensitivity and selectivity (ability to separate a desired signal frequency from other signal frequencies) are dependent on operating temperature, film thickness, porosity and grain size and can be increased by doping with a catalyst made from platinum. Micro-machined multi-element sensors can reversibly and selectively detect carbon monoxide (CO) and nitrogen dioxide (NO_2), by measuring the changes in electrical conductivity due to chemisorption of gas molecules. Detection of CO at concentrations less than 1 ppm and NO_2 below 0.1 ppm is now achievable. These levels are at or below the existing EU legal limits. By integration of metal oxide thin film technology with complementary metal oxide semiconductor (CMOS) compatible device, the selective detection of low concentrations of CO, NO_2 and CH_4 becomes possible in a cost-effective manner (Rickerby & Morrison, 2007).

The nano-structured solid-state gas sensors with superior performance apply advanced micro- and nano-technologies to develop metal oxide gas sensors with increased sensitivity. Fabrication techniques include vapour phase transport process crystal growth and optical, ion and electron beam nanolithography for the selective removal of material. Tin, indium, zinc or tungsten oxides are synthesised in the form of nanowires, nanobelts and nanocombs to increase the effective surface area of the metal oxide exposed to the gas. This can be applied in developing the next generation of selective and stable gas sensors (Calestani, et al., 2005).

Although notable advances have happened in detecting pollutants in the environment, especially in air and water, there is still a need for relatively cheap and light instrumentation for the detection and measurement of nanoparticles. No measuring devices are currently available that can accurately and simply measure all these parameters simultaneously. The potential applications for such a measuring system could be analysis of ultrafine particles in the atmosphere and monitoring of workplace characteristics in nanoparticles manufacturing industries (Rickerby & Morrison, 2007).

5.6. Environmental Remediation

One of the potential areas where N&N can assist towards reaching sustainability goals is environmental remediation. Filtration and purification plants for drinking water supply systems in many cases have encountered problems due to the inefficiency of the active materials. According to Zhang (2003), nanoscale iron particles suggest a new generation of environmental remediation technologies that provide cost-effective solutions to some of the most challenging environmental remediation and cleanup problems. Iron nanoparticles have large surface areas and high surface reactivity. The remediation of soil at contaminated sites can be facilitated by using iron nanoparticles, a procedure that surpasses conventional methods in both efficiency and speed. They also provide enormous flexibility for in situ and practical applications. Research has shown that they are very effective for the transformation and detoxification of a wide variety of common environmental contaminants, such as chlorinated organic solvents, organochlorine pesticides, and PCBs. Modified iron nanoparticles, such as catalyzed and coated nanoparticles have been synthesized to enhance the speed and efficiency of the remediation process.

Metal oxide catalysts play an important role in environmental protection and remediation actions. The specific characteristics of iron oxide nanoparticles have also been exploited for removing arsenic from groundwater. Iron oxide nanoparticles can bind irreversibly arsenic five to ten times more effectively than micron-sized particles and, because of their super paramagnetic properties, can be separated from the purified water by the application of a magnetic field. The nanoparticles can afterwards be retrieved by deactivating the magnetic field to avoid them being released into the environment (Rickerby & Morrison, 2007).

Bonapasta and Filippone (2005) recommend that nanoparticles can be incorporated into paints and coatings to increase their functionality and durability and create ‘‘self-cleaning’’ surfaces. Titanium dioxide has a potential to become an oxidizing agent when exposed to UV radiation and is thus able to break down VOCs, nitrous oxides and other pollutants into less harmful materials. This feature can be exploited as a good environmental remediation measure.

5.7. Chemistry and Chemical Industries

Current trends of production and consumption mainly depend on a continuous flow of materials, including substantial amounts of non-renewable matter, which after a relatively short time period flow back in another shape to the environment. Conventional chemical industry has an important share in this riskful cycle and is often accompanied by unwanted emissions from productions, consumption, and disposal of materials. That's why it is considered one of the most important pollutant industries in the world today and has become a target for both environmentalists and governments (regulation authorities). As a response, the idea of green chemistry has recently come up with the aim of responsible design of chemical products and processes to reduce or eliminate the use and generation of hazardous substances and pollutants. This concept started as a fundamental idea initiated by a few chemists and is currently being taken up by chemical industries and other types of industries.

Among twelve principles of green chemistry that was categorized by Anastas and Warner (1998), there are several requirements that nanotechnologies can potentially fulfill. These principles include:

"1. It is better to prevent waste than to treat or clean up waste after it is formed.
2. Synthetic methods should be designed to maximize the incorporation of all materials used in the process into the final product.
3. Wherever practicable, synthetic methodologies should be designed to use and generate substances that possess little or no toxicity to human health and the environment.
4. Chemical products should be designed to preserve efficacy of function while reducing toxicity.
5. The use of auxiliary substances (e.g., solvents, separation agents, and so forth) should be made unnecessary wherever possible and innocuous when used.
6. Energy requirements should be recognized for their environmental and economic impacts and should be minimized. Synthetic methods should be conducted at ambient temperature and pressure.
7. A raw material or feedstock should be renewable rather than depleting wherever technically and economically practicable.
8. Unnecessary derivatization (blocking group, protection/deprotection, temporary modification of physical/chemical processes) should be avoided whenever possible.
9. Catalytic reagents (as selective as possible) are superior to stoichiometric reagents.
10. Chemical products should be designed so that at the end of their function they do not persist in the environment and break down into innocuous degradation products.
11. Analytical methodologies need to be developed further to allow for real-time in-process monitoring and control before the formation of hazardous substances.
12. Substances and the form of a substance used in a chemical process should be chosen so as to minimize the potential for chemical accidents, including releases, explosions, and fires. "

In many of the requirements of these 12 principles, N&N can play an important role. Nanotechnologies can provide industries with a wide basket of catalytic reagents to substitute stoichiometric reagents. Energy requirements of chemical processes could be minimized at ambient temperatures and pressures with more effective reactions and less material usage at nanoscales. Nanoparticles and nano-structured materials can offer new methods for designing and controlling catalytic functions, including the provision of enhanced activity and selectivity for target reactions. The activity and selectivity of nanoparticle catalysts are significantly dependent on their size, shape, surface structure, and their bulk and surface composition. Thus being able to synthesize particles at the nanoscale with certain physical and chemical properties plays an important role to achieve the goal of catalysis by design. Another potential favor of N&N to green chemistry can be reached with more advances in the bottom-up approach to synthesize nanomaterials that are especially designed to maximize the incorporation of all materials used in the process into the final product. This idea lies deep in the heart of many chemical nanotechnologists, no matter whether they consider molecular manufacturing as extreme technological vision or just outright fantasy.

There are many other nanotechnology applications that address existing sustainability challenges. Nanoporous zeolites allow a slow release and an efficient dosage of water and fertilizers for plants, thus enabling a higher agricultural productivity in countries with prolonged drought periods. Intelligent packaging using nano-composites may permit a longer safe storage of food, especially in regions with warm deserts or other hot spots where cooling is not available. Nanoparticles can improve the efficiency of catalytic converters in cars and reduce their specific emission rates (Fleischer & Grunwald, 2008).

5.8. Water Technologies

Water is one of the main global problems, especially in developing countries. Low quality of water and unsustainable water supplies limit economic development and result in adverse sanitation, health and livelihood conditions. According to UN Millennium Project Task Force on Water and Sanitation (2005) statistics for 2002, more than 2.6 billion people lack access to basic sanitation, and over 1.1 billion people have no access to safe and clean water. Among eight millennium developments goals (MDGs), the seventh goal concerns drinking water and sanitation issues. The target of this MDG for sanitation and drinking water is “7.C: Halve, by 2015, the proportion of people without sustainable access to safe drinking water and basic sanitation” (UNDP, 2007). Thus providing a sustainable clean water source is one of the main challenges of the world today.

The problem is here mainly because of non-technical reasons such as lack of political will, poor governance, poor regulatory frameworks, poor management, institutional constraints and economic issues. But even though non-technical problems are often equal or more important than technical problems, for some regions the situation can be improved by implementing new technologies for water handling (treatment and remediation).

Nanotechnologies can act as helping hands in facing some of the technical challenges and also some of the non-technical problems such as lack of financial resources. Advances in N&N suggest that many of the current technical water problems including water quality and water safety can be resolved or improved by implementing novel methods. Nanosorbents, nanocatalysts, bioactive nanoparticles, nanostructured catalytic membranes and nanoparticle enhanced filters can play an important role in this arena. Advances in the development of techniques to desalinate water are among the most important and necessary. Additionally, nanotechnology-derived products that reduce the concentrations of toxic compounds to standard levels can assist in meeting water quality standards. There have been many advances in the development of novel nanoscale materials and processes for treatment of surface water, groundwater and industrial wastewater contaminated by toxic metal ions, radio-nuclides, organic and inorganic solutes, bacteria and viruses in recent years. Furthermore, some of the problems associated with the development of cost effective nanomaterials for water purification have been resolved (Savage & Diallo, 2005). In addition, nanoscale sensor elements for the detection of contaminants and pathogens in water, and magnetic or catalytic nanoparticles for the treatment of wastewater or water remediation can be applied thanks to nanotechnology developments (Fleischer & Grunwald, 2008).

5.9. Health Technologies and Biomedical Applications

Definitely, the most elaborate and complex nanomachines we know are the naturally occurring molecular assemblies which regulate and control biological systems. For example, proteins are molecular structures with highly specific functions that participate in virtually all biological sensory, metabolic, information and molecular transport processes. It's volume is between one-millionth and one-billionth of the volume of an individual cell and thus can be regarded as a bionanodevice. With this point of view, the biological world contains many of the nanoscale devices and machines that nanotechnologists might wish to imitate. Besides, bio-nanotechnology is a new field concerned with molecular-scale properties and applications of biological nanostructures and so is a trans-disciplinary field between the chemical, biological and the physical sciences. By using nanofabrication techniques and implementing processes of molecular self-assembly, bio-nanotechnology allows the production of materials such as tissue and cellular engineering scaffolds, molecular motors, and biomolecules for sensor, drug delivery and surgery applications (The Royal Society & The Royal Academy of Engineering, 2004, p.19-20).

In particular, according to Sahoo and Labhasetwar (2003) and Uskokovic (2007), nanoparticles have exposed great potential of utilization in mainstream biomedical applications and treatments in a variety of useful ways, including:

- Achieving target-specific drug delivery
- Molecular imaging, biomarkers and biosensors for early diagnosis of pathologies
- Magnetic field-assisted radionuclide therapy
- MRI contrast enhancement
- hyperthermia treatment
- Detection of intracellular molecular interactions with the possibility of developing
- gene and/or cellular metabolic therapy
- Magnetic separation, protein detection and purification
- Magneto-relaxometrical diagnostics and eye surgery

6. Risks and Side Effects of Nanosciences and Nanotechnologies

6.1. General

As mentioned in the previous chapter, nanotechnologies as emerging technologies, may carry potential risks because of their unknown or unpredictable effects on the sensitive systemic parameters of the environment, economy, and society. As was discussed before, the contributions of N&N towards sustainability are very important, both in terms of quantity and quality. They are considered as providing some of the best hopes for future assistance in meeting sustainability challenges such as resource saving, monitoring, remediation, water and energy, and production technologies.

This attribute of nanotechnologies should be utilized in a very careful manner, because logically every technology that can be more influential and effective in the positive way may carry more serious and influential risks that will show off in the future. For the case of N&N, all the potential solutions and contributions to the environment, chemistry, energy and water technologies, and production technologies, may come at a high price. The production, usage, and disposal of nanomaterials and products containing nanomaterials may result in their existence in air, water sources, soil or even living organisms and this might cause certain and irreversible problems in the future.

Most of the research on N&N and sustainability that has been carried out throughout the world is on the benefits of N&N and there have been little initiatives on their potential environmental, health, and social impacts. Therefore, much of the research undertaken so far in N&N, raise more questions than answers, and a more comprehensive and meticulous research system for analysis of nanotechnologies' potential ecological, economic, and societal risks and side effects is needed. In this chapter, a review of research results on the potential environmental and health impacts of nanoproducts is gathered and presented. Also other types of related risks, including the risks that have not been discovered yet, in both forms of known-unknowns and unknown-unknowns will be discussed. Finally, ideas about social and economic impacts of nanotechnologies will be presented and discussed.

6.1.1. What We Do Not Know about Nanotechnologies

As mentioned in the first chapter, when sizes change from macro and micro to nano limits, the cohesive influences of gravitational forces give right to Morse function-shaped electromagnetic forces and quantum effects and when the lower size limit of nanomaterial grains approaches that of regular clusters, quantum effects overcome surface effects and become the dominant factor in defining measured properties (Uskokovic, 2007). Thus size effects in nanomaterials are of great complexity and problematic too and despite a great body of information is available, the understanding of the nature of size effects in nano scales is not so deep and the possibility of prediction in this field is limited too. That's why the knowledge of the size effect nature requires intense research and study in order to highlight the best strategies for nanotechnologies (Andrievski & Glezer, 2001). In summary, the amount and nature of unknowns are so high that there is a great risk of unknown unknowns in the development and implementation of nanoproducts and nanosystems. The potential future impacts or side effects to the environment and the biota are really difficult to discover, and even in some cases impossible to anticipate.

Because of these great uncertainties considering nanotechnologies, many of the favorable features of N&N and their related products come hand-in-hand with fears arising out of the uncertainty or dangers of their ecological threats, environmental effects and the probability of losing control over increasingly destructive characteristics of nanoproducts. Generally, some important nanomaterials have a dual-faced character: some of the characteristics which make them favorable for a number of ecological applications are exactly the properties that are sources of concern. The biokinetics and biological activity of nanoscale particles are different from normal sized particles. They depend on many parameters including morphology (size, shape, agglomeration state, crystallinity), chemistry and surface properties (Fleischer & Grunwald, 2008).

The too many uncertainties and relative ignorance (insufficiency of knowledge) about the potential environmental and health effects, together with the diversity of engineered nanomaterials, imply big challenges for a responsible life cycle of these substances. Another important issue is to ensure that the production methods of nanomaterials are clean and environmentally friendly. In today's production processes, ingredients and raw materials that are known to carry risks to the human health or the environment are often used. It is necessary to ensure that environmental benefits from the use of engineered nanomaterials will not be outweighed by risks from negative effects (Fleischer & Grunwald, 2008). Therefore, it is no longer wise to postpone safety evaluations of nanomaterials and nanoproducts and a strong research program and a proactive approach must be followed to address safety and regulatory issues.

The most important potentially disadvantageous effects of nanotechnologies for sustainability could generally be considered as:

- A realistic vision of unsustainable applications of nanoproducts prospects more harm to the currently endangered global ecosystems.
- The developments and commercialization of nanoproducts could further extend the existing gap between rich and poor and add to existing social problems such as unemployment. This may pose major threats to societies.

From past experiences, history has taught us that predictions generally are wrong. Two of the most well-known precautionary principles state that ‘‘the lack of certainty, given the current scientific and technological knowledge shall not delay effective and proportionate actions to prevent hazards;’’ and “Any discussion of the “Precautionary Principle” must address a complex legal and regulatory situation.” (Petrini C, Vecchia P., 2002/2003). In case of N&N, with the extraordinary amount of uncertainties and complex, rather undiscovered relationship between properties and structures, there is a great difficulty in understanding the whole spectrum of potential effects that will impact the environment, human health, society, and economy. This fact should not retard efforts to research the possible harmful effects of nanotechnologies before they are introduced to the world. Unlike the case of asbestos chemicals (that the interval between knowledge of its harmful effects and the issuing of regulation and standards was approximately a century), all indicators of adverse side effects of nanosystems should be meticulously studied and considered, even if this process slows down the speed of technological innovation. Also according to the Precautionary Principle, any discussion on the production, usage, and disposal of nanoproducts must address a complex legal and regulatory situation.

6.2. Health Risks of Nanotechnology Products

According to Bang and Murr (2002), there is great evidence over the past few years that ultrafine particles and especially nanoparticles in the atmosphere are strong toxins. They are even much more toxic than expected and cause considerable health risks including mortality, asthma complications, chronic bronchitis, respiratory tract infections, ischaemic heart diseases, and stroke. Potential adverse health effects of nanoparticles on humans include their relative persistence in lung tissues up to several months; their potential to pass the blood–brain barrier and to reach brain tissues and induce damage; their absorption into the bloodstream from the skin by uptake into lymphatic channels. There is also a potential for both inflammatory and pro-oxidant activity on the one side, and antioxidant activity on the other side exists for nanoparticles (Uskokovic, 2007).

In a set of toxicological experiments (Service, 2003), nanoparticles made from polytetrafluoroethylene, or PTFE with a 20-nanometer diameter showed dramatic effects when exposed to rats. The rats were exposed to air containing PTFE nanoparticles for 15 minutes and most of them died within 4 hours. In comparison, those exposed to air with PTFE particles of 130 nanometers in diameter did not suffer ill effects. These results show the increased impact and relatively unpredictable properties of materials when their dimensions change towards nanoscales. Thus a slight change in size can have tremendous impact when evaluating potential toxicity relative to living organisms. Another study by Limbach, et al. (2005) states that in low concentrations of inhaled nanoparticles, when the biological uptake processes on the surface of the cell are faster than the physical transport to the cell, the smaller particles are faster to agglomerate in comparison to the larger particles. Larger nanoparticles remain mostly unagglomerated and are thus more resistant and require more time for the body to discard. Therefore in this case, opposite to the previously mentioned case, smaller particles are less harmful than larger particles. There have been familiar cases of materials which ‘‘proved’’ to be harmless to animals but found to have tragic consequences for humans (Uskokovic, 2007). These all indicate that benefit in one way could mean harm in another. It therefore seems impossible at this stage to predict the overall effects of nanoparticles on health. In addition, generalizations of either great harm or complete safety regarding the introduction of nanomaterials and nanotechnologies is a complicated task and must be done based on comprehensive research and with a great care.

A recent report by Oberdörster et al. (2005) indicates that these nanoparameters are able to change body responses and cell interactions, such as a greater inflammatory potential than larger particles, translocation across epithelia from portal of entry to other organs, translocation along axons and dendrites of neurons and resulting nervous problems, induction of oxidative stress, pro-oxidant and anti-oxidant activity of nanoscale particles in environmentally relevant species, binding to proteins and receptors, and localization in mitochondria of the cells. Inhalation of nanoscale particles can translocate out of the respiratory tract via different pathways and mechanisms. When nanoparticles enter the blood circulation, they can distribute throughout the organism, and they are taken up into liver, spleen, bone marrow, heart, and other organs. Generally, these translocation rates are unknown.

All of the above indicate the great uncertainties about nanomaterials effects on health and their related risks, the relatively low amount of information we currently know about engineered nanomaterials, and their short-term and long-term impacts on biota and human health. Further detailed information about different forms of nanoparticles in different media, their behavior and functions, and other information regarding their environmental and health risks will be mentioned in the environmental risks part of the report.

6.3. Environmental Risks of Nanotechnology Products

The production of large quantities of industrial nanomaterials will certainly result in the presence of these materials in the atmosphere, hydrosphere, and biosphere. The composition of these anthropogenic nanomaterials may closely resemble materials for which there are enough information on health and environmental impacts. Generally, nanomaterials are designed to have distinctive properties based on their size, shape, surface functionality relative to mass, and homogeneity. These differences may trigger responses in organisms that differ from those of compositionally similar larger materials. Therefore, even though the properties and impacts of raw or intermediate materials used to produce nanomaterials might be well known from a risk assessment perspective, the safety risks during manufacturing and the environmental fate of nanomaterials cannot be predicted with certainty. Moreover, the environmental effects of nanoproducts, for example if they are absorbed by organisms in the environment and if they can bioaccumulate are still unknown. Although some studies have been carried out worldwide to address the toxicity of nanomaterials and their potential for exposure, statements regarding the impacts of nanomaterials on the environment are still highly theoretical and uncertain. Therefore, a major technical challenge to develop methods for detecting nanomaterials in the environment is needed (Robichaud, et al., 2005 and KEMI, 2007).

Nanoparticles in new environmental surroundings will behave in a way that is too difficult or rather impossible to predict. Fine particles in the atmosphere are mainly located near the surface of the earth and are usually covered with layers of adsorbed water molecules. This increases their catalytic properties that were already high because of their relatively high specific surface areas. Also nanoparticles can travel much longer distances in the air or in the water in comparison to microparticles. Various other chemical products and toxins are almost equally distributed among the organisms in the biosphere, and wide dispersion of industrially produced and engineered nanoparticles in the natural ecosystems can be expected (Uskokovic, 2007 and Bang & Murr, 2002).

Because of the enormous complexity of the environment, it is extremely difficult or even impossible to reach concrete conclusions about the overall effects, impacts and consequences of specific materials or technologies on the environment and natural ecosystems. Thus as a multidisciplinary approach, potential impacts of nanotechnologies and nanomaterials on the aquatic, terrestrial, and atmospheric environments will be discussed in the following parts.

6.3.1. Nanoparticles in Aquatic and Terrestrial Environments

Anthropogenic and engineered nanoparticles are being produced in large and increasing quantities and are being discharged to the aquatic and terrestrial ecosystems in huge amounts. According to the rates and anticipations, both production and discharge will increase in the near future. These nanomaterials should be considered as great potential sources of risks as they might interact with aquatic and terrestrial systems in much unknown ways and are potentially harmful to ecological health. Engineered nanoparticles, including nanotubes, and other nano structures have been considered as potential sources of risk in their life cycle, and have made a strong concern in relation to the natural aquatic and terrestrial environments, because of the following reasons (Hester & Harrison, 2007, p.19):

- These materials are produced with an increasing rate over time, both in research and industrial processes.
- Nanomaterials may behave in a very different way to micro and macro materials, even when structures are chemically similar.
- Their impacts and consequences on ecological and human health are greatly unknown, with absolute unknowns in some dimensions, and potentially severe impacts because of their properties at nano scales.

Although there have been an increase in reviews and reports in peer-reviewed journals, books, and other sources of literature, current knowledge of the behavior, fate, and ecotoxicology of nanomaterials in natural aquatic and terrestrial systems is too limited and the amount of real and final data is too limited. Therefore, there are concerns about potential risks because:

- Natural aquatic systems and their interactions with the terrestrial systems have not been understood in depth and with confidence.
- There is almost no direct knowledge of the behavior of research or industrially produced nanoparticles.
- There is little and very general legislation or few mandatory frameworks for the production or disposal of nanoparticles. Thus their amount and distribution in the aquatic and terrestrial systems is greatly unknown.

Thus discussions and conclusions carry a relatively high uncertainty and clearly time is required to reach more reliable information on the impacts of nanoparticles on aquatic and terrestrial systems. Since there has been very little investigation on the behavior of nanoparticles in natural terrestrial systems, and they are in close relationship with natural aquatic systems, the review and discussion will be mainly about behavior and fate of nanoparticles in natural aquatic systems.

6.3.1.1. General Behavior of Nanoparticles in Natural Aquatic Systems

Most of our knowledge about the behavior of nanoparticles in biological systems has been concluded from biomedical experiments of direct injection, ingestion or atmospheric inhalation; and their subsequent nanopathology (The Royal Society & The Royal Academy of Engineering, 2004). Therefore, the release of nanoparticles into aquatic systems raises the following questions and challenges (Moore, 2006):

- What will be their hydrodynamic behavior? Will nanoparticles behave like larger natural particles?
- How will nanoparticles associate with larger sediments and natural colloidal particulates?
- Will nanoparticles bind organic and metal pollutants?
- What are the routes of nanoparticle uptake into biota?
- Will nanoparticle associated chemical pollutants expose increased toxicity?
- Will particle size and surface properties be important factors in determining toxicity and pathogenesis of nanoparticles in aquatic organisms?

- What will be the implications of nanoparticle exposure for organisms' health and ecosystem integrity?

When it comes to address these questions (the behavior, fate, and ecotoxicology of engineered nanoparticles), there have been just a few reviews and discussions that apparently consider occurring nanoparticles in the aquatic systems. Thus further studies are definitely needed in this area. But on the basis of current knowledge and understanding, the main areas and related factors of concern related to engineered nanomaterials in water systems are presented in the following.

6.3.1.2. Nanoparticles as Potential Aquatic Pollutants

Products and wastes from industries tend to end up in waterways such as drainage ditches, rivers, lakes, estuaries and coastal waters. Therefore, as nanotechnology industries start to come on line with larger scale production volumes, it is inevitable that nanomaterials and their by-products will enter the aquatic environment (The Royal Society & The Royal Academy of Engineering, 2004). This makes it necessary to ensure that we have effective risk assessment procedures in place as soon as possible to deal with potential hazards. In developing a risk strategy for industrial nanoparticles, our past experiences with conventional industrial materials and pollutant chemicals could play an important teaching role.

6.3.1.3. Risks to Aquatic Biota and Ecosystems

Engineered nanoparticles are greatly an unknown quantity in terms of how they will behave in any environment, let alone the aquatic medium. However, we may be able to make some general and reasonable predictions about their potential hazards on the basis of their size, surface charges and chemical reactivity. As they are essentially supramolecular particles, they may also have specific properties due to their biological interactions that are not readily predictable from knowledge of the surface characteristics (Moore, 2006).

6.3.1.4. Nanoparticles Interactions in Water Systems

Natural aquatic systems are not pure water bodies and contain a huge variety of complex suspended and heterogeneous organic and inorganic materials from weathering, microbiological growth and other processes. It is accepted that accurate understanding of the morphology, composition, and structure of the particles, suspended materials, and colloids in the water systems is essential in understanding their role and behavior in the water ecosystems (Lead, 2005). The natural and engineered nanoparticles in water systems have the potential to interact with these diverse materials and consequently change their properties and behavior. The interaction can potentially be extremely complex firstly because of different properties of nanoparticles in different formulations, shapes, and sizes and secondly because of the variability in solution conditions in the water ecosystems.

6.3.1.5. Interactions with Nutrients, Pollutants, and Pathogens

Naturally occurring nanoparticles can act as key chemical species interacting with pollutants, nutrients, and pathogens in natural water systems. This property can be explained by increasing specific surface areas and thus novel properties at smaller sizes. Furthermore, it has been seen that nanomaterials affect the rates of chemical behavior in the natural aquatic systems (Hester & Harrison, 2007, p. 29).

6.3.1.6. Effects on Pollutants and Pathogens Fate and Behavior, Easy Transportation of Pollutants, and Complicating Water Treatment Operations

Engineered nanoparticles also affect fate and behavior of the pollutants and pathogens as they will act as a complex formed with the nanoparticles. Therefore, engineered nanoparticles will facilitate transport by providing a binding phase for the pollutant and thus preventing absorption to the stationary solid phase. These pollutant nanoparticles complexes are small enough to transport through pores in the porous material (Hester & Harrison, 2007, pp. 29-30). This causes great problems for water treatment plants and the water filtering and purification systems.

6.3.1.7. Risks to Human Health via Water and Aquatic Systems

Accidental or routine release of industrial effluents containing nanomaterials in waterways and aquatic systems may lead to exposure of humans to nanoparticles via skin contact, inhalation of water aerosols, and direct ingestion of contaminated drinking water or particles adsorbed to vegetables or other foodstuffs (Daughton, 2004). Other indirect exposure means include ingestion of organisms such as fish and other marine biota as part of the human diet. Molluscs such as edible shellfish and snails absorb these released nanoparticles from aquatic ecosystems and are known to accumulate suspended particle and sediment-associated conventional pollutants. Therefore, they can be easily transported to humans while being eaten directly or indirectly as in poultry food (Moore, 2006).

6.3.2. Nanoparticles in the Atmosphere

Currently, the most important source of the exposures of nanomaterials to humans is the air which people breathe. Nanoparticles are abundant in the atmosphere. They have been distributed in the atmosphere since the fire and combustion processes – that generate nanoparticles - have been used for the first time. Thus, in most of the densely populated geographical regions of the world, presence of nanoparticles is highly elevated above the unpolluted background concentrations. There have been several comments that because of their high degree of toxicity, nanoparticles are the reasons for a large number of adverse effects due to exposure to airborne particles. The main sources, properties, and health and environmental impacts of the release and presence of nanoparticles in the atmosphere, will be discussed in the following sections.

6.3.2.1. Sources of Atmospheric Nanoparticles

Nanoparticles in the atmosphere can generally be either primarily or secondarily produced. The sources of each of these categories would be as follows.

6.3.2.2. Primary Nanoparticle Emissions

These nanoparticles are directly emitted in the form of nanomaterials. The sources of this type of nanoparticles include traffic, fossil fuel heating systems, and industrial combustion processes. The particulate matters with diameters less than 100 nano meters ($PM_{0.1}$) are emitted from combustion processes in internal combustion engines, burners, kilns, and furnaces and are distributed into the atmosphere. Thus the biggest source of primary nanoparticles emissions in the atmosphere of urban districts would be transportation and in the atmosphere of industrial districts would be industrial combustion and other nanomaterials used in industries handling nanomaterials or advanced chemical reactions.

6.3.2.3. Secondary Nanoparticle Emissions

These particles are formed in the atmosphere from the condensation of low volatility vapors from oxidation processes of atmospheric gases. These totally new nanoparticles are formed by a process called “Atmospheric aerosol nucleation”. Size distributions of nanoparticles and concentrations of gases in particle nucleation can be measured directly in the atmosphere. However, although several ways for particle nucleation have been proposed, it is still unclear which of the mechanisms of particle nucleation dominates in the atmosphere. Recently, the nucleation and growth of nanoscale atmospheric aerosol particles have been observed with modern techniques in several atmospheric environments, including the lower stratosphere, the free troposphere, the continental boundary layer just above Earth's surface and coastal environments (Kulmala, 2003).

6.3.2.4. Emission Sources

Information on particle size distributions and concentrations in the atmosphere of different types of districts is very limited and especially very few data on the nanoparticles have been recorded. In a study by Shi et al. (2001), measurements indicate that road traffic and stationary combustion sources generate a large number of nanoparticles of diameters <10 nm. Measurements at 4 meters distance from the kerb of the road and downwind from the traffic (more than 25 meters from the kerb) show that nanoparticles with diameters less than 10 nm account for more than 36–44% of the particulate concentrations. It is notable that research on urban emissions of particulate matter shows a greater proportion coming from the transportation sector than is shown in the research on national emissions levels.

Different types and sizes of nanoparticles are emitted from traffic sources. According to (Hester & Harrison, 2007, pp. 40-1), those nanoparticles together with the sources they are emitted from are:

- Fine fractions ($PM_{2.5}$) which are assumed to be emitted mainly from engine exhaust;
- The coarse fractions ($PM_{2,5-10}$) that are assumed to arise mainly from abrasion sources such as tires, brakes, and road surface wear.

Research results by Harrison, et al. (2004) show that $PM_{2.5}$ emission factors are of the order of 0.2-1.0 g/km for heavy vehicles and 0.01-0.03 g/km for light vehicles, though these rates definitely depend on speed, load, and driving conditions. Emission factors for particle concentrations range from $2.7*10^{13}$/km for light vehicles and about 10^{15}/km for heavy vehicles, dependent on speed, load, and driving conditions. Tests for the difference between roadside (PM_{10} concentrations about $34.7*10^{-6}$ g/m^3) and corresponding urban districts (PM_{10} concentrations about $23.2*10^{-6}$ g/m^3) samples indicates mean mass increases about $11.5*10^{-6}$ g/m^3 of PM_{10} and $8.0*10^{-6}$ g/m^3 of $PM_{2.5}$ for the four site pairs in the studies. Furthermore, the roadside particle increment is mainly made of elemental carbon, organic compounds and iron-rich dusts.

Furthermore, there is a huge amount of emissions from other combustion and elevated temperature processes and equipments utilizing oil, coal, fuel oil, and natural oil as fuel in different industries and services. Moreover, indoor activities such as gas and electric cooking act as main sources of indoor nanoparticles with diameters normally ranging from 16-69 nm (Hester & Harrison, 2007, pp. 41-7).

6.3.2.5. Chemical Composition of Atmospheric Nanoparticles

According to measurements of the chemical composition of particles with diameters less than 100 nm in California conducted by Cass, et al. (2000), the average chemical composition of the ultra fine particle samples was 50 % organic compounds, 14 % trace metal oxides, 8.7 % elemental carbon, 8.2 % sulphate, 6.8 % nitrate, 3.7 % ammonium ion, 0.6% sodium, and 0.5% chloride. The most abundant metals present in these nanoparticles were Fr, Ti, Cr, and Zn.

6.3.2.6. Risks to Human Health

Atmospheric nanoparticles may be responsible for some of the health problems due to air-pollutant exposure. They directly enter the body through inhalation or skin tissue. Information about toxicity and potential adverse health effects of atmospheric nanoparticles are the same as general health risks of nanotechnology products which have been discussed earlier in section 6.2.

6.3.2.7. Insufficiency of Knowledge

Knowledge about sources and concentrations of nanoparticles is relatively good just for the cases of traffic emissions and atmospheric formations in the nucleation process. Yet there have been very few studies on ultra-fine particles chemistry, non-traffic combustion processes, and engineered nanoparticles (such as from industries during production phases or in the consumption phase) in the atmosphere. This insufficient knowledge in the nature of atmospheric nanoparticles raises the uncertainties related to their effects on human health and biota’s well-being, aquatic and terrestrial systems, and regional ecosystems. This highlights the important research activities on atmospheric nanoparticles structure, behavior, and impacts that have been neglected so far. Thus there is a great need for research on atmospheric nanoparticles encompassing sources, types, concentrations, structures, and health and environmental impacts.

6.4. Socio-economic Impacts

Advancements in N&N and related products and services promise to have huge impacts on human society, wealth and peace in coming years. Among the expected dramatic advancements are increases in IT and computer efficiency, human organ restoration using engineered tissues, designed materials made from direct assembly of atoms and molecules, and the emergence of entirely new phenomena in chemistry and physics. Thus the possible utilization of these technical developments in different industrial, medical, and security applications raises new related ethical, legal, social, and economic issues and challenges (Roco & Bainbridge, 2001). Therefore, there is a strong need for research in potential social implications of nanotechnologies. By the way, some basic suggestions and general directions on maximizing potential positive impacts and minimizing possible negative impacts are possible at this stage. Second-order consequences of the emerging technologies coming in this arena shall also be considered and the related compensation measures shall be addressed. In the following parts, some of the significant probable socio-economic impacts of nanotechnologies will be discussed.

6.4.1. Rebound Effect

Although nanotechnologies light new ways for resource saving, there is a big risk of increased consumption. One source of probable increased consumption could be lower prices of commodities. This will occur in a certain time period after commercialization of nanoproducts as a result of using less resource and raw materials, implementing novel production techniques, and less labor participation in the production phases due to advanced technology. Thus, as it has happened in a lot of the services and products such as in case of mobile phones, cars, clothes, etc., the savings in resource consumption during usage might be offset by increased consumption during manufacture and disposal. This means an increased usage and disposal of nanomaterials to the environment and could become a so-called “rebound effect”.

6.4.2. Other Socio-economic Impacts

There have been very few studies on social and economic impacts of N&N so far. When it comes to the high rate of advances in the fields of N&N and their related products, services, and consequences on society and economy, the great need to obtain knowledge about potential changes and side effects for compensation and anticipation activities is justified. There is a great vacancy in this arena (social consequences) and extensive research must be conducted on the economic and social impacts of nanoproducts.

From a simple and philosophic point of view, there are some probable socio-economic impacts which could be discussed. As the dimensions dealt with get smaller with a factor of 10 by the power of something in comparison with conventional technologies, the rate of developments and achievements can naturally become highly elevated. As it can be seen up to now, there is a very rapid rate of advancements in the fields of N&N and their related products and services. The ideas of self-cleaning glasses, non-iron textiles, no-wash clothes, and self-recovering asphalts were not even imaginable until a few years ago.

When the mentioned and other novel ideas come to market, they can drastically affect business routines and alter social and economic norms and paradigms. In most of the cases, these influences would be of an unknown nature and to some extent totally unpredictable. These drastic changes are able to take adjustment opportunities from society and might finally lead to severe social and economic malfunctions. For example, some major traditional industries and services might go bankrupt and unemployment, economic instability, and fundamental disorders in the social and economic life cycle would happen.

The newly arrived nanoproducts might be of such delight that they result in the emergence of new economic giants and altered paths of financial turnover. The advancements and commercialization of nano-enabled products may extend the existing social gaps and raise other social problems such as unemployment, poverty and insecurity. These may further threaten the societies. Moreover, the social and economic infrastructures might encounter dramatic changes to a state of irreversible changes in social and economic paradigms. The advent of new habits and procedures and disappearing of some of the old ones could be another result. After that, secondary and later social consequences such as poverty, corruption, social insecurity, etc. might take place and this cycle implies a wholly impacted and disturbed social and economic system.

All of the mentioned probable consequences justify proactiveness and the start of socio-economic investigations regarding the advent of nanomarkets and nanoproducts.

7. Discussion

Nanotechnology is considered to be one of the most prominent emerging technologies of the 21st century and has been described with several main characteristics such as transformative technology, enabling technology and the technological revolution. Although it is supposed to act as one of the main helping hands towards general prosperity and sustainability goals due to the totally novel abilities in all branches of science and technology, it is still under question whether nanotechnologies can become sustainable or not. While the adverse experiences of emerging technologies in the past have made a cynical preconception in the public and political parties, it can be counted as one of the advantages of Nanosciences and Nanotechnologies (N&N) to utilize the previous experiences towards a sustainable approach.

Because of the extraordinary abilities, N&N have the potential for great contributions towards sustainability in most of the challenging branches including resource efficiency, technical contributions and acting as an enabling technology, energy technologies, environmental monitoring and remediation, chemistry, water technologies, health technologies, medical applications, and other commodity industries and services. There have been too many dark spots in the way of most of these fields that after the advent of N&N, a new ray of hope has lightened the ways with novel solutions and techniques.

Decreasing the grain size of a material to nano limits results in the appearance of either new or changed properties. The Morse function-shaped electromagnetic forces and the quantum effects conquer cohesive influences of gravitational forces. Also the specific surface to mass ratio increases substantially, resulting in increased proportion of interface defects and their impacts on dependent properties. Furthermore, for the lower size limit of nanomaterial grains, quantum effects overcome surface interactions and become the dominant factor in defining measured properties (Uskokovic, 2007). Thanks to these new parameters, making nanomaterials with novel properties and extraordinary abilities is possible. However, none of the mentioned phenomena are totally understood yet and despite a great body of information, the understanding of the nature of size effects in nano scales is not deep and the possibility of prediction in the field of N&N is too limited (Andrievski & Glezer, 2001). This lack of knowledge in the fundamentals makes predictions of nanomaterials behavior and necessary anticipations for compensations and adjustments much more uncertain, and in a lot of cases, impossible. Therefore, the hidden properties of these totally new materials and their actions in the complicated systemic environmental relations - in the context of incomplete data - carry extraordinary high risks.

The current heady combination of high-level investment, fast technological progress and exponentially increasing commercialization of nanotechnologies, easily point us to the perspective of significant impacts on society and the environment over the coming decades. despite many research initiatives on N&N throughout the world, there have been just little research on the potential environmental and health impacts of N&N and even much less research have been conducted on their related impacts on economy and the society.

There are still too many uncertainties about the adverse health and socio-ecological impacts of N&N. As mentioned before, N&N carry potential unknown risks because of their unknown and unpredictable effects on the sensitive systemic parameters of the environment, economy, or society. This is a frightening fact that in most of the cases, the scientific society is not even able to predict the effects and impacts of nanomaterials. The lack of fundamental knowledge on structure-function relations in nano dimensions and the trial-and-error essence of N&N have dramatically increased the probability of occurrence of totally unforeseeable events and thus has raised the level of complexity.

Recent research results prove that engineered nanoparticles might have tremendous consequences for the natural ecosystems. They can act as potential pollutants with the ability of interactions in water systems and the atmosphere with drastic consequences on human and biota's health. Among the results of the investigation on the adverse impacts of nanotechnologies, the most important fact that has been acquired is the relative uncertainty and lack of knowledge about the several risks and side effects of N&N. This insufficient knowledge in the nature of nanoparticles entering atmospheric and aquatic systems raises the uncertainties related to their effects on human health and biota's well-being, aquatic and terrestrial systems, and regional ecosystems. It is evident that the important research activities on nanoparticles structure, behavior, and impacts have been neglected so far. Thus there is a great need for research on atmospheric, aquatic, and terrestrial nanoparticles encompassing sources, types, concentrations, structures, and their related health and environmental impacts.

However, despite the understanding of the existence of these extreme risks (some even totally unknown) and the basic knowledge we have acquired in potential adverse effects of nanotechnologies on the environment, biota's and human health, and the complex socio-economic systems, anthropogenic nanomaterials are being produced in increasing quantities and are being discharged to the aquatic, terrestrial, and atmospheric ecosystems in huge amounts. According to predictions (Hester & Harrison, 2007, p. 19), both production and discharge will increase in the near future.

One of the reasons of this hurried market development of nanomaterials would be the wide range of advances and facilities that come from the developments of N&N in almost all of the challenging fields plus some emerging fields. However, the expected contribution of N&N advances towards sustainability can happen if and only if N&N development is supported by critical investigations on potential harmful effects of new N&N technologies. Otherwise, several of these fantastic abilities of N&N may turn into serious harmful effects on nature and society. Thus the possible utilization of these advances in different industrial, medical, and security applications raises new ethical, legal, social, and economic challenges. Besides ecological impacts, because of the wholly novel and unpredictable properties, there is a great risk of deep socio-economic consequences such as rebound effects, shifting social habits and routines, changing the economic paradigms without proactive adjustment, increasing the gap between rich and poor, and other miscellaneous (and sometimes irreversible) social alterations. Thus a meticulous real-time monitoring (with high cautiousness) is necessary from the very beginning so that the global and local societies do not face irreversible fundamental damage. Whether such dramatic changes may happen or we are able to harness the unwanted consequences is a very controversial issue.

The other and perhaps most important reason of the heady commercialization of nanotechnologies without considering adverse consequences would be economic growth which results in market pressure. The historian McNeill (2000, pp. 334-6) believes that "the overarching priority of economic growth was easily the most important idea of the twentieth century." Is he right in his assessment? There are still very few who question the importance and high priority of economic growth and perhaps it looks a logical approach. This approach has isolated the economists and market concepts from nature and has made extreme devotion of business to economic growth. Although this attitude is understandable, it would be sad if the stakeholders that run the economy do not realize the fundamental natural limits or lose the courage to change the current deplorable situation (Daly & Farley, 2004, p. xxi).

This is the current philosophy of the world economy that could be so-called "growth fetish" (McNeil, 2000, pp. 334-6) and according to the idea of some of the current economists is accompanied by extreme short-sightness of the humankind, especially economists and business owners. With this economic pattern, further improvements and all of the measures would act as temporary remedies. Therefore, a new market concept that internalizes today's non-market values (such as ecological and societal health, sustainability, etc.) should gradually substitute current economic paradigms.

However, with too many stakeholders involved in this concept, it is really difficult to change the current market and social trends. Improvement of the conditions requires participation of all stakeholders and effective interaction among them. The global society comprising people, international authorities, governments, NGOs, the scientific society and small and large companies will have to refine the current economic patterns step by step. Here, of course, some companies and individuals who have specific privileges from existing patterns will be reluctant and might even act against necessary changes. Important social forces to foster in this development are increased public pressure, more effective regulation and increased international and local cooperation.

The public (people) are among the main stakeholders of the complex affairs of N&N risks and the necessary changes in social patterns and trends. People must be effectively informed about both positive and negative consequences of emerging technologies. This public communication – from the early stages - makes public sense of trust and alertness. Conscious people that put value on their own living and have responsibility about next generations will gradually change their habits and step forward to the establishment of modified relations and improved routines. This public motivation forces firms to change their attitudes and act in a sustainable way, not to lose their profit or destroy their public image. Public awareness not only forces companies but also makes the international community and local governments to consider sustainability aspects in relation to the developments of N&N. The fact that people of the world feel responsible for their environment and next generations facilitates the proactive ratification and execution of sustainable N&N regulation issued by international authorities and governments. It also makes performing the measures of improvement much easier and more effective. It is only with this real-time monitoring and proactive approach that society finds the opportunity for adjustment and is able to escape future catastrophes.

To finalize this discussion, it is necessary to consider several stakeholders that are involved in the developments of N&N. Controlling current and future developments of N&N and their social, economic, and ecological impacts, and leading them to the desired directions – to become sustainable - requires a basket of systematical scientific, technical, legal, and social actions. This is to ensure that N&N as a promising, revolutionary, and untested affair is taking the safe way, or at least its related contributions towards society and the environment overweighs its adverse consequences, probable risks and impacts. Reaching a concrete agenda for these improvement measures is not easily possible and an approach relying on public communication, techno-scientific research, proper and real-time regulation, and a globally democratic, non-self-privilege based attitude is demanded. Conducting high quality non-market research on N&N issues including fundamental structure-function characteristics, health and environmental friendliness with a life cycle approach, and the industrial ecology (industrial symbiosis) approach with consideration of socio-ecological affairs, and implementation of the related results in practice is both crucial and of foremost importance.

However, as we have not taken this way yet and because of lack of knowledge, for the best conditions, it will be based on iteration and trial-and-error. Thus social and ecological fluctuations are natural to happen. Therefore, it is recommended that novel solutions, based on a global thinking, undertake a local test period and after evaluation of their results, decision about whether to change, quit, or spread the solutions in a global scope takes place. But still the questions about long-term impacts on society, economy, and environment can not be answered with certainty. Most of the novel and state-of-the-art solutions that seem ideal in the moment of decision-making prove to be completely wrong in longer terms and the case of N&N is not an exception. Especially because of the complexity and unknown relations in N&N, this problem is of excessive importance. Although calling for research on fundamentals and changing the current attitudes – as described in the text - could become really helpful, but the problem of unpredictable long term consequences will be still there. Therefore, if we want the related developments of N&N, we have to pay the price; the price of informing ourselves better about potential harmful effects of N&N.

8. Improvement Suggestions

Nanotechnologies have been described with several main characteristics such as transformative technology, enabling technology and the technological revolution. After the bad experiences about technical and scientific advances in past decades, such as for the cases of nuclear power, asbestos, and genetically modified food, there is an increasing skepticism about the ability of scientists, industries and governments to ensure the safety of new technologies. Therefore, such a heady combination of high-level investment, fast techno-scientific progress and exponentially increasing commercialization of nanotechnologies, easily points us to the potential significant impacts on society and the environment over the coming decades (Maynard, 2007).

It would be rational if enthusiasm over the rate of advancements being achieved gets tempered by concerns over possible risks and unforeseen consequences of this new branch of technologies, including unforeseen or poorly managed risks to human health, society, and environment. In this regard, a basket of systematic, scientific, technical, legal, and social actions must take place to ensure that this promising and revolutionary technology is safe, or at least its related contributions towards society and the environment overweighs its adverse consequences, probable risks and impacts.

8.1. Public Communication

As nanotechnology moves in the direction of every-day utilization and commercialization, not only discussion and actions on preventing adverse consequences occurring at an unusually early stage in the development phase is needed, but also further actions beyond conventional risk management to incorporate public communication should seriously take place. It is only with this clear attitude from the very beginning that people get improved knowledge and will consider nanotechnology and its related changes in society and industry as reality. This makes a factional and reliable basis for the social responses and relations to establish better attitudes and right values so as the necessary adjustments in society with a general feeling of reliability, trust, and acceptance will take place.

The public (people) are among the main stakeholders of the complex affair of N&N risks and the necessary changes in the social patterns and trends. People must be effectively informed about both positive and negative consequences from the early stages. This makes them alert and these conscious people will feel responsible for next generations. This public motivation not only changes societal habits, modifies relations, and improves wrong routines but also forces firms to change their attitudes and act in a sustainable way. Furthermore, global public awareness forces international community and local governments to consider sustainability aspects in relation to the developments of N&N. The fact that people of the world feel responsible for their environment and next generations facilitates the proactive ratification and execution of sustainable N&N regulation issued by international authorities and governments. It also makes performing the measures of improvement much easier and in a much effective manner. It is only with this real-time monitoring and proactive approach that society can adjust itself in an appropriate way.

8.2. Regulation

Up to now, regulation and legislative frameworks on N&N and their related products and services have been really weak as could be called “no regulation”. As science and technology evolve and society develops, regulatory frameworks towards environmental, legislative, cultural, societal, and ethical issues must cope with. In this regard, ratifying a moratorium on the production and release of new nanomaterials would be as unwise as grasping to the old set of existing regulations that were useful before the advent and commercialization of N&N. Therefore, as ethics, self responsibility, and society’s spontaneous responses can not be relied on as a sole or even main part to deliver nanoproducts to markets in a safe and beneficial way in the interests of human and environmental excellence, a rational balance between innovation, ethics, and regulatory precaution should be achieved through a state-of-the-art methodology. While gaps between technology (based on science) and ethics may occur, they can be balanced through implementation of a multi-disciplinary decision-making process that integrates humanistic, environmental, ethical, societal, and techno-economic values (Uskokovic, 2007 and Randles, 2008).

The trickiest part here is the nature of N&N which is characterized by relative ignorance and unknown relations, making totally unforeseeable and unanticipated surprises of form, shape, scale, and probability of events. The other features that connect the governance of N&N with unprecedented problems are:

- N&N applications and their consequences and impacts can not be predicted from the basic sciences;
- Nanoscience takes place at the overlaps of all the scientific disciplines.

These attributes of unpredictability and unanticipated consequences, including unforeseeable rebounds, unknown thresholds, and hidden tipping points, are the essence of complex systems of which N&N systems can be considered as a particular class (Randles, 2008). Therefore, the issue of governance for the case of N&N is not a new problem but should be a continuous challenge under these conditions. Another difficulty in regulation for N&N is that on the one hand ratifying regulation and mandatory frameworks at very early stages, including the extreme response of imposing moratoria potentially damps innovation and may stop the emergence of beneficial technologies. But on the other hand, a strategy of silence or so-called “wait and see” may easily result in late regulation and perhaps catastrophic events that could have been anticipated, mitigated and handled more effectively if a proactive approach had been adopted.

Thus N&N regulation should consider all of these challenges and make a balance through implementation of a multi-disciplinary decision-making process that integrates humanistic, ecological, ethical, societal, and techno-economic values. The early but very general response to this need would be the European Commission’s recommendation on code of conduct for responsible nanoscience and nanotechnologies research, published on 7th of February 2008. It is devised on the notion of increased cautiousness and responsibility on the side of all social actors (businesses, governing institutions, and civil society). The general principles are meaning, sustainability, precaution, inclusiveness, excellence, innovation, and accountability. Considering good governance, it states: “Good governance of N&N research should take into account the need and desire of all stakeholders to be aware of the specific challenges and opportunities raised by N&N. A general culture of responsibility should be created in view of challenges and opportunities that may be raised in the future and that we cannot at present foresee”. We can call this approach real-time regulation and seems to be a good approach towards complex N&N affairs (Commission of the European Communities, 2008). The general principles from the European Commission recommendation on a code of conduct for responsible nanoscience and nanotechnologies research are summarized in table 2.

Table 2 - General principles of the European Commission recommendation on code of conduct for responsible nanoscience and nanotechnologies research. Source: Commission of the European Communities, 2008.

Meaning	N&N research activities should be comprehensible to the public. They should respect fundamental rights and be conducted in the interest of the well-being of individuals and society in their design, implementation, dissemination and use.
Sustainability	N&N research activities should be safe, ethical and contribute to sustainable development serving the sustainability objectives of the Community as well as contributing to the United Nations' Millennium Development Goals. They should not harm or create a biological, physical or moral threat to people, animals, plants or the environment, at present or in the future.
Precaution	N&N research activities should be conducted in accordance with the precautionary principle, anticipating potential environmental, health and safety impacts of N&N outcomes and taking due precautions, proportional to the level of protection, while encouraging progress for the benefit of society and the environment.
Inclusiveness	Governance of N&N research activities should be guided by the principles of openness to all stakeholders, transparency and respect for the legitimate right of access to information. It should allow the participation in decision-making processes of all stakeholders involved in or concerned by N&N research activities.
Excellence	N&N research activities should meet the best scientific standards, including standards underpinning the integrity of research and standards relating to Good Laboratory Practices.
Innovation	Governance of N&N research activities should encourage maximum creativity, flexibility and planning ability for innovation and growth.
Accountability	Researchers and research organizations should remain accountable for the social, environmental and human health impacts that their N&N research may impose on present and future generations.

Legislation with regard to nano-enabled products places the same responsibility on companies as it does for chemical products and articles. The scientific limitations in risk assessment, particularly on risks from the inhalation of nanoparticles, imply that companies should apply special precautions in the development of nanomaterials in order to limit exposure to humans and the environment. They must classify substances based on available information and in cases where no information on a substance’s health or environmental hazards exists, current EU classification of health and environmental hazards for the substances at a larger scales shall apply for the nano-enabled products as well. Although current legislation considers nanomaterials, regulations need to be claerified as nano-enabled products may cause particular problems both in risk assessment and risk management. Rapid rate of development of the area together with the great lack of knowledge about health and environmental risks call for precautionary measures. It is likely to involve complementing the EU regulatory framework with regulations on nanomaterials, including rules about testing methodology and extent to which companies must test nanomaterials' health and environmental hazards (KEMI, 2007).

8.3. Call for Research and Investigations

Although N&N are expected to make drastic changes in the coming decades, there is a severe lack of knowledge about N&N and its related risks in all aspects. Most of the research already conducted in the fields of N&N has been for commercial purposes and contributions towards various industries and businesses. Yet the share of non-market based N&N research has been too small. The same holds true for non-oriented random discoveries and the several impacts of nanotechnologies on society, environment, and human health. Thus, there is strong demand for extensive and novel research in all of the N&N fields, especially the following.

8.3.1. Nanomaterials Fundamental Structure-Function Characteristics

As mentioned beforehand, when dimensions approach to nano limits, the physical rules that predict the characteristics change and quantum effects become the dominant factor in defining measured properties (Uskokovic, 2007). That is why size effects in nanomaterials is of great complexity and relatively unknown character and the possibility of prediction in this field is too limited (Andrievski & Glezer, 2001). Thus the knowledge of the size effect nature requires intense studies and orientated research programs.

8.3.2. Health and Environmental Friendliness with a Life Cycle Approach

There are too many uncertainties about the potential environmental and health risks and the diversity of engineered nanomaterials imply big challenges for a responsible life cycle of these substances (Fleischer & Grunwald, 2008). Therefore, ensuring the health and environmental friendliness of production processes and methods, and safety of ingredients and raw materials, is essential in nano research activities. It is also necessary to ensure that environmental benefits from the use of engineered nanomaterials during the whole life cycle and with a cradle-to-grave perspective in the long term, will not be compensated by risks from negative effects. According to Fleischer & Grunwald (2007), despite many claims from scientific communities that life cycle assessment methodology should be used for assessing existing and expected developments in nanotechnologies, there have been only few research projects and papers that have actually done so. Therefore, it is urgent to conduct safety investigations on long term impacts of nanomaterials, their complete production cycle (from extraction of raw materials to production and manufacturing), and their related consumption and disposal phases. Indeed, a strong research program and a proactive approach must be followed to address safety and regulatory issues with a life cycle approach.

8.3.3. Pure and High Quality Non-prescribed Research

Although academic style of research had been generally free from external direction until 1970s, it has been somewhat influenced from external business and political orientations in the past 30 years and a continued increase in R&D investments. Freedom to carry out flexible, curiosity driven research results in outcomes not foreseeable at the outset and this kind of research often challenges accepted ideas and introduces novel methods and new fields of study and research.

Research policy in the past 30 years has given growing support for short-term goal-oriented scientific research projects, with pressure applied on researchers to predict and demonstrate the future application of their research work. This approach of rigid scopes of research and preconceived objectives carries the risk of restricting freedom, limiting research direction, and stifling rather than stimulating the creativity needed for scientific discovery. The power of big companies and their major share and influence for funding research programs, together with conforming to trends that result in career establishment, instead of focusing on the long-term results, represents a risk of passiveness in the contemporary scientific society. Most of the significant steps in the evolution of science, including the discoveries of quantum mechanics, the theory of relativity, and molecular biology, were not derived from market needs, external demands, or prescribed technical-scientific objectives (Uskokovic, 2007 and Linden, 2008).

Therefore, after about four decades of conducting intensive but market-oriented research, it is time for the governments and international authorities to apply routines to start to increase funding research on non-market purposes and based on health, safety, sustainable development, and innovative attitudes. There is a crucial need for funding on free, non-predetermined, pure and high quality research in all of the scientific fields including N&N. It's only through this type of research that real evolutions and purely novel achievements, better solutions for the future, and more beautiful horizons for a better mutual human-environment world could be reached and prospected.

8.3.4. The Industrial Ecology (Symbiosis) Approach with Consideration of Socio-ecological Affairs

Despite early calls for a life cycle approach in technical and industrial products and services, in practice, we are still only marginally better at understanding whole systems – from cradle to grave. Considering a life cycle approach to N&N developments, proactive management of related risks and adverse impacts, and greening of the extraction, production, consumption, and disposal infrastructures, little has happened in practice. It is necessary to understand that industries – in this case, the nanotechnology industries - are acting as organisms on the Earth and thus ignoring their long term impacts among their whole life cycle will definitely result in occurrence of irreversible and adverse consequences for the whole system. Current acceleration that is apparent in N&N systems continues to decouple from social and institutional regulation unless something is really done, sooner rather than later. Thus there is not just a role here for industrial ecology but it is an ethical necessity to contribute to the development of logical and responsible reactions to the current social and environmental challenges (Allenby & Rejeski, 2008).

To some extent, the complexity of these technology systems and the unknown-natured relations between them and socio-ecological effects, highlights both strengths and weaknesses of industrial ecology, in that the systems-based and trans-disciplinary nature of the field provide a more comprehensive framework within which they can be understood. But simultaneously, the weakness of industrial ecology in the face of this complexity is also inevitable. To the extent that industrial ecology is understood as a basket of main methodologies such as material flow analysis, energy analysis, and life cycle assessment, it is thus detached from the larger cultural context (Allenby & Rejeski, 2008). Therefore, there is a great need to conduct research on understanding the technology-society-environment relations and to mimic ecological symbiosis with a broader perspective. This means that novel approaches should not only make a closed loop industry (including nano-industry), but also should consider society and ecosystems relations with the new paradigms and relationships that will take place.

9. Conclusions

The distinctive characteristics of materials at nanoscales enable us to reach extraordinary capabilities and solve a lot of techno-economic, social, and ecological problems. However, the shallow understanding of fundamental properties of nanomaterials and their behavior in the context of natural ecosystems, along with high levels of uncertainties and lack of knowledge, both in the form of known-unknowns and unknown-unknowns, prospects the drastic potential risks of the development of Nanosciences and Nanotechnologies (N&N) to socio-economic, health, and ecological domains. Among extensive research and high investments in N&N, most of them focus on development of new techniques for the production of novel nanomaterials and there are very few studies that investigate fundamental characteristics of nanomaterials and their long term effects and behavior in the context of the real world. Therefore, public communication from the early stages parallel with conducting high quality non-prescribed scientific research on N&N issues, including fundamental structure-function characteristics, ecological friendliness with a life cycle perspective, sustainability, and the industrial ecology approach with consideration of social, economic, and ecological aspects, together with implementation of the related results in practice, is strongly recommended.

Acknowledgement

I would like to give my greatest gratitude to my supervisor Assoc. Prof. Björn Frostell for all his support, encouragement, guidance and useful suggestions throughout my master thesis. The discussions we had, his systematic approach, and his novel ideas not only helped me with my thesis work but also gave me a different perspective and vision for my future life and career.

I also wish to thank all the staff of Industrial Ecology department of KTH for the education and support they provided during my master program of Sustainable Technology.

I would heartedly like to thank my parents and my sister for their continuous and unlimited love and support throughout my life.

Last but not least, I would like to thank all my friends.

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TRITA-IM 2009:14
ISSN 1402-7615

Industrial Ecology,
Royal Institute of Technology
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