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Economical potential and safety of nanomaterials

Dr. Gian Carlo Delgado[1]

Interdisciplinary Research Centre on Sciences and Humanities,
National Autonomous University of Mexico.

C/Manuel López Cotilla 1544 Int. 301.
Col. Del Valle. Del. Benito Juárez.
México, D.F. 03100
Tel. +52.55.56230271

Summary

The capacity of manipulating matter at the nanoscale has opened a great potential for diverse type of applications and novel innovations, going from new materials for the textile, packaging or food industry, all the way to sophisticated medical procedures and treatments. The economical potential seems to be of major order and it starts to be evident by the increasing public and private spending on nanoscience and nanotechnology research and development; the rising patent registrations all over the world; the growing market quotas and perspectives on the use of nanomaterials in production process, goods and services; etcetera.
Still, nanotechnology potential carries with it significant concerns as those regarding its safety and adequate use and assimilation by society. Therefore, experts have pointed out the need of an international standardization of the production processes of nanomaterials worldwide; the embracement of (eco)nanotoxicology research; as well as the implementation of responsible and "smart" regulatory frameworks in the sense of guarantee the safety of nanomaterials to the public, and thus of nanoproducts and nanosolutions, while invigorating the development of nanoscience and nanotechnology. The mentioned above should be understood, from a political and economic perspective, as the need for a fully accountability, communication and management of nanotechnology aspects and implications with the purpose of avoid or reduce unnecessary costs; define responsibilities; and maximize the socialization of benefits and opportunities.

[1] Researcher of "The World in the XXI Century" program of the Interdisciplinary Research Centre on Sciences and Humanities at the National Autonomous University of Mexico. Member of the National Research System (SNI).

This paper reviews the main economical indicators of nanotechnology development and potential while offering an assessment on the most relevant nanomaterials safety concerns and proposals for its accountability and management nowadays.

Key words: nanotechnology, nanomaterials, nanotoxicology, standardization, posnormal science.

1. Introduction: a brief review of nanomaterials economical potential.

Four are the main technological fronts at the beginning of the 21st century: 1) information technologies; 2) biotechnology / synthetic biology; 3) new energy technologies; and 4) nanotechnology (Delgado 2002, 2006 and 2008a). The latest, and even more, all of the mentioned technologies as a whole -or what has been called *converging technologies*- promise to revolutionize the world (Roco and Bainbridge 2001; Nordmann 2004; Zonneveld 2008; Kjølberg *et al* 2008). This means, for a starter, a deep or significant transformation or modification of production processes and of social relationships. Thus, some impacts could be of major order.

Nanotechnology in particular, or the capacity to manipulate matter at the nanoscale (a billionth of a meter or 10^{-9} m) with the purpose of developing novel materials and devices, has already arrived with a burgeoning future prospective. Its potential covers from new materials useful for the textile, packaging, food or transportation industries; nanodevices and nanomaterials for sophisticated medical procedures and treatments or for cutting edge telecommunication and information technologies; all the way to more effective security and military innovations (Roco and Bainbridge 2001 and 2003; National Research Council 2002; European Commission 2005; Berube 2006; Delgado 2008a; etcetera).

In this sense, it doesn't surprise the growing rhythm of public and private spending on research and development of nanoscience and nanotechnology. Public spending worldwide has been estimated from 430 million dollars in

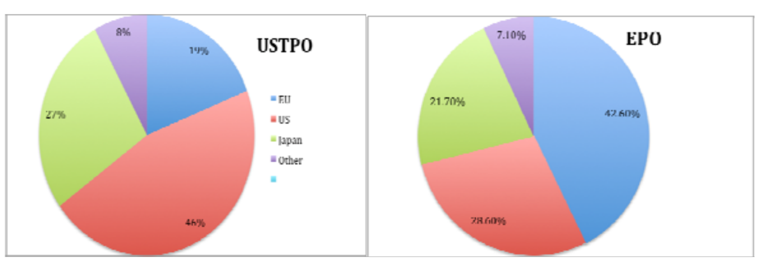
1997, to 3 billion dollars in 2003; 4.6 billion in 2004; 5.9 billion in 2005 and 6.4 billion in 2006 (Delgado 2008b: 89, 91). Private spending is calculated at 4 billion dollars for 2004; at 5 billions in 2005 and at 6 billions in 2006. For 2007, private and public spending on nanoscience and nanotechnology combined is expected to be around 14 billion dollars (Ibid: 91).

US' *National Nanotechnology Initiative* (NNI) expenditure for 2008 is estimated to be nearly in 1.5 billion dollars, an ammount to which is to be added the funding coming from States Initiatives and other indirect contributions. European Union's *7th Framework Programme* (2007-2013) approved 3.45 billion euros for "nanosciences, nanotechnologies, materials and new production technologies". It corresponds only to a third of the total European spending on nanotechnology. In addition, the German annual spending is set around 330 million euro; the French at 150 million euros and the British at 50 - 75 million euros yearly. *3rd Science and Technology Basic Plan* of Japan (2006-2010) has allocated 5 billion dollars for nanotechnology research and development; that is around a billion per year (Ibid: 90).

On what respects to patents, the average annual growth rate from 1996 to 2002 is approximately 15% for the case of the European Patent Office (EPO). Similar tendencies are recorded for the US Patent and Trademark Office (USPTO) from the mid 1990s (Igami & Okazaki 2007: 13). However, countries' shares in nanotechnology patents from 1992 to 2001 at the USPTO and the EPO give to US the first position, followed by Europe and Japan (see image 1).

Image 1

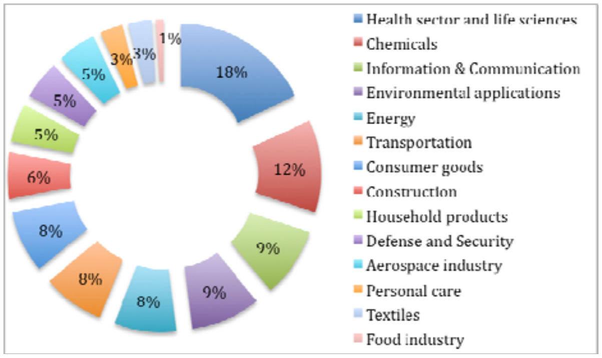
Nanotechnology Patentes (1992-2001)



Source: Glänzel *et al* (2003). *Nanotechnology Analysis of an Emerging Domain of Scientific and Technological Endeavour.* Steunpunt O&O Statistieken. Belgium. July: 46.

By 2007, nanotechnology spending concentrated on applications areas such as the health sector and life sciences with 18% and chemicals with 12%. Other areas were similarly relevant among them, including energy, communication and information technologies, transportation, and environmental applications (see Image 2). As a result more than 400 products by companies from more than a dozen of countries and around 600 nanotechnology raw materials, intermediate components and industrial equipment items used by manufacturers were identified by the same year (Maynard 2006: 41; www.nanotechproject.org/inventories/consumer).

Image 2
Main Nanotechnology Aplication Areas (2007)



Source: Nanoposts (2007). *Government Policy and Innitiatives in Nanotechnology Worldwide 2007*. Canada: 39.

The data seems to be consistent with the market share and estimations on products sales that at some level use nanotechnology. Diverse sources calculate that the nanotechnology market by 2004 was around 12.9 billion dollars and by 2006 nearly on 50 billions dollars. Estimations for 2008 are around 150 and 100 billon dollars on product sales; for 2010 at a half a trillion dollars and by 2015 between 1 and 2 trillions (Delgado 2008b: 89). For example just the agricultural nanotechnology applications market is expected to growth from 7 billion dollars to 20 billions by 2010. A similar spectacular growth is predicted for the nano-packaging market which is supposed to growth from around a billion dollars in 2005, to 5 billions by 2011 and 14 billions by 2013.

Such expectations, or what some called the *nano hype* (Berube 2006), clearly entail a social and technological construction of a defined *imaginary* that can, or not, accomplish their own forecast and that may, or not, produce non-expected outcomes, either positive or negative. In any case, what seems to be clear now is that nanotechnology potentiality is real and that it may produce profound effects on the economy, society and the environment as not ever seen before. Accordingly, society should dialogue and define, in a responsible way, how to develop such a technological front; for what means; in which timeframe and priority; and instead of what (if that is the case –for example thinking n some underdeveloped countries).

2. Implications and safety of nanomaterials

Nanotechnology excitement, but also uncertainty, has stimulated an increasing introduction of economical, societal, political, ethical and environmental aspects to the scientific and public debate. This is due to the expectation of complex, novel and even uncertain consequences of some nano-innovations. While indeed some will not come true, others certainly will in the short, medium or long term. However, it is to notice that even if some of such an aspects can or could be anticipated, nevertheless, others might be completely unexpected.

In addition, it can be acknowledged that there is usually a restraint on the type of concerns evaluated until now since there is the tendency on focusing on plausible negative implications and risks directly related only to technical and technological aspects. That trend tends to leave aside other issues such as social assimilation processes or social misuses of nano-innovations (including the mishandling of nanomaterials during production processes). In other words, while it is plausible that some nanomaterials turn out to be unexpectedly toxic once liberated into the environment or on the lung run as its saturation increases or as a cause of negligence, there is also the possibility that *nanosolutions* do not get socialized on time causing unnecessary health and environmental costs. The latest can also happen if nanotechnology benefits get poorly socialized as a consequence of an existing hypothetical context of social distrust and misunderstanding.

Such issues can be partially tackle in conjunction if standardization and eco-toxicological issues of nanomaterials are taken seriously into account and, thus, if they are properly regulated at the national, regional and international levels. Seeking those objectives means, on one side, that scientific research is done to determine the safety of nanomaterials as good as it can be done (accordingly more funds and a regulation/cooperation schemes are needed); and, on the other, that an informative and open dialogue process is desirable in order to inform the public, clarify unfounded concerns and, thus, (socially) "immunize" nanotechnology against failure. This blueprint might work in view of the fact that responsibility is assumed and defined and because eventual risks can get socialized while benefits maximized.

Even though, pitfalls can occur. However, social response might not be reactive but instead more centered and consensuated.

Considering the above, it is then crucial to delineate the role and dimension of social sciences and humanities in the understanding and assessing of nanotechnology social, ethical and environmental implications (see: Strand 2001; Schummer 2005; Delgado 2008a; Alhoff *et al* 2008; Alhoff & Lin 2008; Bennett-Woods 2008; etcetera). The exercise, however, is difficult since nanoscience and nanotechnology, as stated above, is a highly complex, uncertain and not-yet-socially-assimilated research field in which values and stakes may be high and in dispute. As put it by Brian Wynne,

> …The future is uncertain. This is eminently true in the case of undeveloped technologies involving the application of knowledge yet to be discovered. Both long- and short- term impacts will include uncertainty that is likely to be irreducible and unquantifiable, in the sense that precise, valid and reliable predictions cannot be made. To the extent that some impacts may even be unimaginable before they appear, the uncertainty also takes the form of present ignorance about the future (Wynne 1992: 111-127).

For example, on what respects to the direct technical/technological implications there is a concern among the scientific community on the safety of nanomaterials since it is believed that some could provoke non-desirable consequences. As recognized by some official reports and other sources, the risks coming from the proliferation of nanomaterials are there because of the soaring ignorance on prognosticating the interaction of nanostructures with the environment and the whole food chain (see: Roco and Bainbridge, 2001; Roco & Tomellini, 2002; EPA, 2002; Roco & Bainbridge, 2003; Royal Society & The Royal Academy of Engineeering, 2004; Department for Environment, Food and Rural Affairs, 2005). Consequently, as accurately expressed by Maynard:

> …there is no reason to assume that nanotechnology will be different from other industrial innovations when it comes to having the potential to present both benefits and risks to human and environmental health (Maynard, 2006: 8).

Nora Savage, an environmental engineer at the Environmental Protection Agency (USA) acknowledges for instance that:

> …compounds for which we have toxicological, fate/transport, or bioaccumulation/bioavailability data may have to be reassessed due to the fact that at the nanoscale, chemical and physical properties are often drastically altered […] We are just at the beginning of our knowledge base in this field…we are learning that: 1) these materials need to be well characterized and standardized so that research results can be compared; 2) using engineered nanomaterials may not be as appropriate as examining the consumer products in which they are incorporated; and 3) it is not enough to state that engineered nanomaterials embedded or fixed in a matrix poses no environmental or human hazard –the end of the product needs to be considered, if the product is burned, placed in a landfill with reactive liquids and gases, recycled, etcetera (personal communication in: Delgado, 2006).

On the other side of the Atlantic, Dr. Jurguen Altmann agrees by stating that:

> …concerning fates and effects of nanoparticles in the body and the environment, there is an obvious (and generally acknowledge) lack of acknowledged; all the more remarkable is the fact that nanoparticles are being put into consumer products relying just on the licensing for the material, even though every overview article states that: 1) at the nanoscale matter shows different properties; and, 2) nanoparticles can enter through pores where larger ones cannot (Ibid).

The literature on the type of issues just mentioned is already considerable and the most relevant has been nicely reviewed by the ISO Technical Report (TR 12885) on “Health and safety practices in occupational settings relevant to nanotechnologies" (ISO, 2008). Generally, the main concerns are related to: nanoparticles' translocation ability after an initial exposure; the potential for greater dermal and gastro-intestinal uptake of nanoparticles when compared to larger ones; the reality that nanoparticles seem to be more biologically active; nanoparticles' potential to cross cell membranes and interact with subcelluar structures; and the capacity of causing cell/tissue systemic toxicity. Just to illustrate it is worth to mention:

- the work of Wiesner on the colloidal characteristics of nanoparticles and its potential of function as carriers of toxic material such as hydrophobic wastes or heavy metals (Quoted in: Colvin, 2002);

- the publications of Günter Oberdorster *et al* on the impacts of nanostructures in the air which disclose, on one side, that carbon nanoparticles can penetrate through the respiratory lobules of rats and reach their brain, and on the other side, that some potential implications of C_{60} on microbes are of concern as experiments showed that presence of C_{60} inhibits microbes' growth and breathing (Oberdorster, G., *et al*, 2004; Oberdorster, G., *et al*, 2002);

- the research of Eva Oberdorster and her colleagues on fullerenes' toxic impacts on fish metabolism (particularly the case of the C_{60}) (Oberdorster, E., 2004)[2];

- the results of Yang and Watts experiments that showed that aluminium nanoparticles presence may be related with the growth delay of some crop roots (case of corn, soybean, or carrot) (Yang, and Watts, 2005);

- the report of Lovern and Klaper on the impacts to biodiversity of different titanium nanoparticles and C_{60} concentrations in water, which concluded that even the lowest concentration of those nanostructures cause the dead of a considerable percentage of the *Dophnia Magna* (Lovern, 2006);

- the paper of Hamilton *et al* related to engineered carbon nanoparticles and which states, based on in-vitro and in-vivo mouse model studies, that they alter the macrophage immune function and initiate airway hyper-responsiveness (Hamilton *et al*, 2007).

- the findings of Craig Poland *et al* in the UK regarding the effects of carbon nanotubes introduced into the abdominal cavity of mice which result on an asbestos-like pathogenicity (Poland *et al* 2008); among others.

[2] A fullerene is the third allotropic form of carbon. It was discovered in 1985.

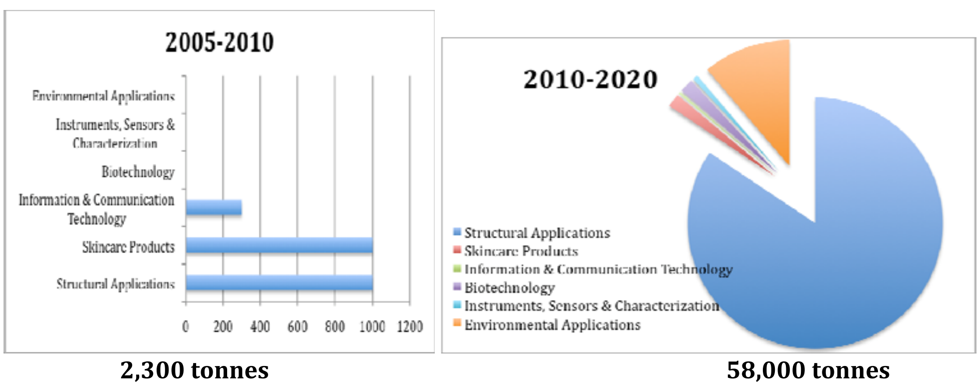
Considering the above, the words of Ken Donaldson, Professor of Respiratory Medicine at the University of Edinburgh, UK seem to be appropriate:

> ...We are already exposed to ["natural"] nanoparticles of different kinds. We already recognize that there is some ill-health associated with these exposures […] The nanotechnology revolution may design particles that are very different chemically from the ones we are exposed to, and they might have very different properties that made them more harmful. We should be vigilant (Kirby 2004).

The statement is of major relevance, mainly for the reason that the amount of nanomaterials being produced is rising exponentially (see image 3), but also because the absence of proper characterization and standardization of nanomaterials, as well as of risk assessments and risk management schemes associated to nanomaterials and nanoinnovations, can be too costly in all terms: economically, politically, socially and environmentally. Unnecessary

Image 3

Estimated Annual Global Production for Engineered Nanomaterials



Source: Royal Society and the Royal Academy of Engineeering (2004). *Nanoscience and Nanotechnologies: Opportunities and Uncertainties*. London, UK.

costs can be generated at diverse levels and scales.

For example,

1) costs can increase within production processes due to the lack of quality standardization of nanomaterials, affecting the producer's finances and market share, as well as impacting the international commerce and finally consumers;

2) toxicological aspects won't be suitably assessed since results will differ from one to another for the "same" material. Negative health implications could then be costly and unnecessary.

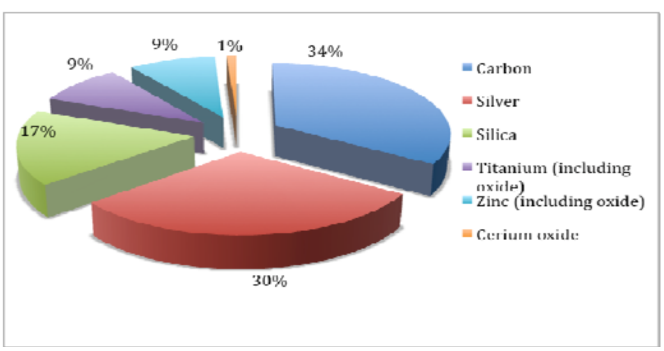
3) environmental costs that could be anticipated might not be detected in advance or on time. Cleaning could be too costly and not always possible. Hence, costs and implications that could be avoided will have to be confronted and assumed.

4) social costs of an irresponsible nanotechnology development (once reveled by avoidable risks cases) may induce social rejection and fear, financial restrictions to nanoscience and nanotechnology public research; consumer boycotts to nanoproducts; etcetera.

Yet, being "vigilant" on what respects to the toxicology of nanomaterials as such, is clearly an issue that can only be monitored by the *expertise*. This means that it is something that should be unravelled by the scientific community, starting with the urgent need of characterizing and standardizing nanomaterials – mainly those based on carbon, silver, silica, titanium and zinc; the most used in consumer products nowadays (see image 4). This is due to the fact that nanomaterials toxicity will not change as a product of ethical or social related aspects; it is a physical, chemical and biological property of the material as such, meaning that the potential health risk of a substance is usually related to the magnitude and duration of the exposure; the persistence of the material; the inherent toxicity and the susceptibility or health status of the person or of living forms.

Image 4

Nanomaterials used in consumer products (2006)



Source: Maynard, Andrew (2006). *Nanotechnology: A Research Strategy for Addressing Risk*. Woodrow Wilson International Center for Scholars. US.

However, something different -and valuable- is to query not only on the ethics of scientific practices, but also on the criteria and parameters to be used on risk assessments and other type of evaluations on this or that use of nanomaterials. On a different level but useful as well, are those aspects related to, for example, how nanotechnology accomplishments will be communicated, promoted and supported; how eventual controversies will be solved; how the risks and benefits of nanotechnology will be socially distributed in both, developed and underdeveloped countries; among other aspects.

Accordingly, nanotechnology may carry several benefits but also multifaceted societal and technological pitfalls and *unintended* and/or *unpredictable consequences* (or what it is called "risks"). This is a situation, a *posnormal* situation, in which most of the implications cannot be discussed and determined by science alone (Ravetz 1971; Funtowicz & Ravetz 1990; Ravetz 2006; Funtowicz & Strand, forthcoming). This is due, as Funtowicz & Strand (forthcoming) writes, to the fact that:

> …when there is considerable scientific uncertainty, such as when the facts are highly uncertain, or when experts are in strong doubt, the modern model [Thomas Kuhn, 1970] is no longer the unique rational design choice for the relationship between science and policy (Ibid).

For this reason, nanotechnology development is an *open process* that cannot be totally predicted and controlled (Delgado 2006 and 2008a). Therefore, nanotechnology assessments need to be enriched by developing "non-conventional perspectives" that instead of trying to avoid or neutralize "risk", on the contrary, aim to learn to live with it by trying to "manage" it. This implies that the knowledge of science experts is not enough anymore to characterize, evaluate and solve all nanotechnology's problems or implications. However it is of course too relevant.

On this regard, international experts agree that for threshold toxicological effects, quantitative determination of 'safe' levels includes the following steps,

> …1) the determination of a No-Observed-Adversed-Effect Level or a 'Benchmark Dose' using animal or human exposure-response data; 2) the extrapolation of animal levels to human levels by recongnizing the significant uncertainties introduced by such extrapolations; and 3) the derivation of occupational exposure limits upon consideration of technical feasibility, variability and uncertainties of models and approximations used and acceptable level of risk (ISO 2008: 43).

Though, since nanotechnology is an emerging field, asserts the ISO,

> …there are uncertainties as to whether the unique properties of engineered nanomaterials also pose unique occupational health risk. These uncertainties arise because of gaps in knowledge about the factors that are essential for evaluating health risks (e.g., routes of exposure, translocation of materials once they enter the body, and interaction of the materials with the body's biological systems)…[consequently]…the occupational health and safety effects of new nanomaterials are mostly unknown […] our abilities to accurately predict the impact of some nanomaterials exposures on worker health are limited at this time […] In addition, the capability of the human body to recognize and appropriately respond to most nanomaterials is essentially unknown at the moment (ISO, 2008: 2).

In order to reduce such lack of knowledge, it is identify from the scientific community, the urgent need for standardizing reference materials and the development of what the ISO calls a "Best International Standards Practices in Materials Specifications" (Ibid). In addition it is recognized the necessity of developing international protocols for toxicity and for evaluating environmental impacts of nanomaterials (including recycling and disposal).

One of the main reasons for calling for the actions just mentioned above is due to the fact that the existing toxicity studies have been conducted, most of the cases, with test materials which were not well characterized, usually because of technological limitations (ISO 2008: 44). Consequently, research studies are not always comparable and cannot be generalized. The panoramic gets even more complex when considering the increasing number and amount of nanomaterials as well as of companies that produce each one.

What seems to be true is that in the process, as correctly pointed out by Ravetz:

> …the most technical methods, at the core of the research activity, are crucial in the shaping and selection of our knowledge and ignorance, and do so as an indirect reflection of politics (Ravetz, 2006: 103).

Thus, other actions have been proposed by governments in areas such as the understanding of the implications of nanomaterials on the environment and human health; the development of proper instrumentation, metrology and analytical methods; as well as on exposure/risks assessments and life-cycle analysis (see table 1 for a summary of the case of the US *National Nanotechnology Initiative* agenda).

Table 1
Main actions proposed by the Strategy for Nanotechnology Related Environmental, Health and Safety Research (2007).

Instrumentation, Metrology and Analytical Methods	Nanomaterials and the Environment	Nanomaterials and Human Health	Human and Environmental Exposure Assessment
1. Develop methods to detect nanomaterials in biological matrices, the environment, and the workplace. 2. Understand how chemical and physical modifications affect the properties of nanomaterials. 3. Develop methods for standardizing assessment of particle size, size distribution, shape, structure, and surface area. 4. Develop certified reference materials for chemical and physical characterization of nanomaterials. 5. Develop methods to characterize a nanomaterial's spatiochemical composition, purity, and heterogeneity.	1. Understand the effects of engineered nanomaterials in individuals of a species and the applicability of testing schemes to measure effects. 2. Understand environmental exposures through identification of principle sources of exposure and exposure routes. 3. Evaluate abiotic and ecosystem-wide effects. 4. Determine factors affecting the environmental transport of nanomaterials. 5. Understand the transformation of nanomaterials under different environmental conditions.	1. Understand generalizable characteristics of nanomaterials in relation to toxicity in biological systems. 2. Understand the absorption and transport of nanomaterials throughout the human body. 3. Develop methods to quantify and characterize exposure to nanomaterials and characterize nanomaterials in biological matrices. 4. Identify or develop appropriate in vitro and in vivo assays/models to predict in vivo human responses to nanomaterials exposure 5. Understand the relationship between the properties of nanomaterials and uptake via the respiratory or digestive tracts or through the eyes or skin, and assess body burden. 6. Determine the mechanisms of interaction between nanomaterials and the body at the molecular, cellular, and tissular levels.	1. Characterize exposures among workers 2. Identify population groups and environments exposed to engineered nanoscale materials. 3. Characterize exposure to the general population from industrial processes and industrial and consumer products containing nanomaterials. 4. Characterize health of exposed populations and environments. 5. Understand workplace processes and factors that determine exposure to nanomaterials.

Source: NNI (2007). *Strategy for Nanotechnology Related Environmental, Health and Safety Research*. National Nanotechnology Initiative. Washington, D.C., US.

Still, it is to notice that for the case of US, just 1% of the National Nanotechnology Initiative budget is designated to highly relevant nanotechnology risk research. In 2005 the ammount was around 11 million dollars from a total of 30 millions which included research relevant to health and safety issues (Maynard, 2006: 3). This is less than the 40 millions that were claimed to be allocated for such research activities by the NNI until that year (Ibid).

On what respects to studies on ethical, legal and societal aspects of nanontechnology, it is to be said that the need is great but the offer still limited, specially when compared to the dimensions and rhythm of scientific and technological development of nanotechnology. Limitations are indeed due to nanotechnology's stage of development and of socialization; to the lack of strong and coordinated research stimulus; and mainly, to the fact that experts on such issues are still limited. More support to such type of research should be implemented.

3. Final thoughts

At the bottom, what we seem to confront is how we define *risk* and how we assume to be *precautious and responsible* in developing "good" nanotechnology, meaning the one that is intended to be safe and socially useful.

Accordingly and as a counterpart of the degree of complexity and uncertainty that characterizes 21st Century science and technology development, it is recognized a process of encouragement -even though not necessarily- of what seems to be a deeper appraisal of diverse aspects of technology development and its relation to society. Ravetz insight on science and technology and its uncertainty, or what he calls *posnormal science* (Ravetz, 1971), is crucial at this juncture in terms of: who needs it; who will benefit from it; who will pay its costs; what happens when it goes wrong; who will regulate it, how, and on whose behalf; etcetera.[3]

[3] The so called "post-normal science is one case in point as well as the science, technology and society (STS) studies or the studies of the ethical, legal and social implications (ELSI), among others.

From a *posnormal* perspective, it is obvious that for the case of nanotechnology, we must have to deal with the type of questions just mentioned above, through an open social dialogue while avoiding hype discourses. This is because the worst we can do is to carry on with a blind or biased approach of nanoscience and nanotechnology research and development or what can be seen as the formalization of a *socio-technical construction of ignorance* (Ravetz, 2008).

Thus, among the main issues that seem to be urgently needed in order to take a responsible development and use of nanomaterials into practice is the wide integration of the risk management notion and of (nano)ethics (still to be fully outlined and materialized – see: Strand & Nydal, 2008) into research procedures and policy making; the creation of a proper and socially settled regulatory agenda; the coordination of efforts and the formalization of different kinds of incentives for research on environmental aspects of nanomaterials and for societal, legal and ethical aspects of nanotechnology; and the stimulation and spreading of a public informed dialogue through conventional and novel mechanisms of communication.

What will happen is yet to be seen, however there are some actions and discussions that suggest that the international scientific and policy making communities, as well as some part of the public, are interested, in some degree or another, on a positive nanotechnology outcome.

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