

Scientific Reports on Decision Making



Nanotechnology: What is it and how will it affect us?

A non-technical review of nanotechnology
from a Catalan perspective – its potential
economic and social impacts and the potential role of public policy.



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NANOTECHNOLOGY: WHAT IS IT AND HOW WILL IT AFFECT US?

A non-technical review of nanotechnology from a Catalan perspective — its potential economic and social impacts and the potential role of public policy.

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NANOTECHNOLOGY: WHAT IS IT AND HOW WILL IT AFFECT US?

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THE ADDED-VALUE OF INDEPENDENCE



As a result of the FCRI activities repair, the Foundation is today a competent and expert resource capable of providing with necessary elements of analysis and understanding of science and technology to the Catalan research and innovation system. It complements the promotion functions of our system and, notably, those of scientific knowledge dissemination.

Within the framework of challenges and commitments agreed on the Catalan Agreement for Research and Innovation (CARI), signed in November 2008, the FCRI provides a structuring and independent feature enabling the interinstitutional connection to co-ordinate activities and programmes and, consequently, to draw up impartial studies to assess needs and research outcomes, regulation and impact.

The capacity for projection and service to the Catalan research and innovation system, which partially derived from our public/private nature, enables us to take a position on expertise, legitimacy and ability to reach consensus to co-ordinate analysis and study groups on research development. Over the next few months, actions for changing the Catalan research system to make it more efficient and more effective, as the CARI states, will shape the FCRI with new characteristics. In every case, however, the ability to reach consensus and the impartiality will be ensured to still have competent resources for analysis and forecasts.

In the early 2008 we launched the ICPDE reports collection. You have at your hands a new report devoted on nanotechnologies, one of the most multidisciplinary frontier fields of science and at the same time with more challenges to the productive structure, to society, and to people's lives, which generates controversies and questions.

As you will see in these pages, the ICPDE reports aim to ensure that research outcomes, players, resources and international research trends are accessible to citizenship and all kinds of people and R&D&I stakeholders. The current FCRI's task as an advisory and foresight institution, and the whole of its activities, are being developed as a truly neutral point which will be enriched with other actions in the same line, such as our in-depth liaison with the EPTA network (European Parliamentary Technology Assessment), the co-operation with STOA (Science and Technology Options Assessment) as well as with the Parliament's Advisory Council on Science and Technology (CAPCIT), which is responsible for informing and providing advice on science and technology for the Parliament of Catalonia.

The FCRI becomes a body catalysing initiatives from the system. It is a flexible and improved structure which is independent professionally and politically speaking and it is put at the service of Catalonia. I am absolutely sure that we will get the most within the new research structure in Catalonia.

Joan Comella
Director
Catalan Foundation for Research and Innovation

INFORMATION ON DECISION MAKING... ON NANO?

Last year, the University of Harvard recommended the book *Physics for future presidents*, a great sales success, dealt with, in a plain understandable language, the importance of some physical processes useful to understand and to make decisions on energy sources, to support research or risks in the space race.

In Barcelona at the same time, the Catalan Foundation for Research and Innovation (FCRI) launched the collection "Scientific Reports on Decision Making (ICPDE) with the same objective: getting relevant information on a technology or a scientific area across to public opinion in a plain but also rigorous language.

Naturally, it is necessary information to take position, make decisions on options or to learn more about a subject in order to create opinion. Especially in scientific and technological subjects, which we can understand and assess them if we have a specialised information, which is often not accessible to everyone. Internet and the new technologies also enable us to access information, sometimes so much that it is difficult to differentiate and select.

In the face of these needs and serving the purpose of bringing scientific knowledge closer to society, the FCRI launched the ICPDE collection that aims to provide informed and layman public with information and expert and independent analysis to facilitate decision making and strategic positions in science and technology; to help them to learn about consequences of new technologies and to foster the research and innovation development in Catalonia.

Decision making on subjects related to scientific knowledge requires information on advances and technology and science fields that are relevant for society and should be included in the political agenda. It is also necessary to learn more about controversy, causes and consequences, relationships with stakeholders involved.

Technology Assessment is a concept that embraces different forms of policy analysis on the relation between science and technology and typically includes policy analysis approaches such as foresight, economic analysis, systems analysis and strategic analysis.

The ICPDE reports are designed for open-minded and dynamic public audience from institutions in Catalonia taking political decisions to institutions enforcing, assessing or explaining those decisions to the other citizens.

So, as Director of this FCRI's collection, I am very pleased to present the 2nd ICPDE report "Nanotechnology: what is it and how will it affect us?" that will surely become a useful tool for those in need.

Judit Castellà
Director of Programmes
Catalan Foundation for Research and Innovation



FOREWORD

Sometimes when some facts are produced, they are able to change radically perception and to help us to target problems and opportunities from new perspectives. This is the case of nanotechnology. Richard Feynmann, Nobel Physics Prize winner, gave a talk in an American Physical Society meeting at the Caltech (California Institute of Technology), in December 1959, the title of which has been made famous, "There's Plenty of Room at the Bottom", where the scientist considered the possibility of direct manipulation of individual atoms and its consequences. These ideas started to be realized in the early 1980's when Binnig and Rohrer, two researchers at IBM's research labs in Zurich, designed the first scanning tunneling microscope allowing imaging solid surfaces with atomic scale resolution. The scientific community immediately understood the utmost importance of the discovery and they received the Physics Nobel Prize in 1986.



Since then, the expected scientific and technological benefits and the social impact of nanotechnology have continued to increase exponentially. EU and US have taken the lead, but also the developed and emerging countries, by drawing up initiatives and communications and structuring policies to back the nanotechnology's development. Catalonia has not excluded from this and has endorsed the commitments agreed on by EU in the Lisbon (2000) and Barcelona (2002) meetings that focused on boosting an economic growth model based on knowledge and nanotechnology is plunged deep into this scheme. Nanotechnology, as the Research and Innovation Plan for Catalonia 2005-2008 already pointed out, is one of the seven priority areas of the sectoral and technological strategy that had to be encouraged to reach the appropriate standards of competitiveness in strategic sectors as well as a medium-term competitiveness strategy in all producing sectors.

But, what exactly nanotechnology is? Which areas does it cover? What impact has it on business world? How does social welfare affect people? What potential risks are involved? Answers to the questions should be clear and understandable to help policy-makers to be aware of the nanotechnology's importance and now and here to design lines of action to turn scientific development into technological and innovative development in business sector.

This FCRI's report responds in a clear, rigorous and pedagogical manner to the above-mentioned questions. I would stress on 3 issues. The report compares the impact of nanotechnology on society with the one of the greatest scientific discoveries of the 19th century: electricity. I think that it is an appropriate comparison because it is expected that nanotechnology will be integrated into all human being activities. This spirit fits my personal perception that nanotechnology is called to become the next industrial revolution. The second point is the impact of nanotechnology on industry. Nanotechnology should be seen as an opportunity of added value on the technologies' improvement, but, in addition, the producing sector must be prepared to encompass new applications the basis of which lie in nanotechnology. The key issue is that many applications do not require sophisticated technologies but new ideas. Nanotechnology in many fields is at an affordable cost. Moreover, there is still time to actively involve in this revolution and the Catalan

Agreement on Research and Innovation (CARI) must be the basis of the roadmap. The third issue is the control of potential risks. Particularly the EU are investing many efforts in this field and, as outlined in the Commission Communications about the European strategy on nanotechnology, are fostering proactive policies to safeguard health and security of citizens.

The document that you have in your hands joins the ICPDE collection. A range of recommendations that I think are right and appropriate follows at the end of the text. It is no easy to draw up a report on a vast and transversal subject such as nanotechnology and to deal with the disparity of issues taking up under the umbrella of nanotechnology.

In short, this document and its References section should help politicians to underpin their decisions on sound arguments based on a good knowledge of subject matter, as this document tries and very much succeeds.

Jordi Pascual
Director
Catalan Institute of Nanotechnology

ABOUT THE AUTHOR



Born in Melbourne, Australia, Boaz Kogon studied biochemistry, information technology and applied mathematics at the University of Western Australia before pursuing a corporate career in agrifoods, working with both small firms and large multinationals with postings in Perth, Auckland and Tel-Aviv. He has recently completed an MSC in the Economics of Science and Innovation at the Barcelona Graduate School of Economics.

He is currently Project Manager at the Institut Catala de Nanotecnologia in Barcelona and also acts as a freelance consultant in marketing & business strategy, primarily in agrifoods and biotech. His previous posts include R&D Manager at AION Diagnostics and General Manager Marketing at Milne AgriGroup

both in Perth, Western Australia.

NANOTECHNOLOGY: WHAT IS IT AND HOW WILL IT AFFECT US?

Governments and industry are pouring billions of euros into developing nanotechnology, while the media and consumer goods companies use the word “nano” with ever-increasing regularity. Yet nanotechnology is well understood by very few outside the scientific community even though its impacts, both positive and negative, are likely to affect many aspects of our lives within a decade. This report aims to give the non-scientist a brief yet comprehensive overview of nanotechnology – what it is, what its impacts will be on industry, the economy, the environment and society - and suggests some actions that can be implemented on a regional basis to address the key issues of concern, with particular reference to Catalonia.

KEY WORDS

Nano; nanotechnology; particles; R&D; technology transfer

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EXECUTIVE SUMMARY

Nanotechnology is a general term referring to many different technologies and applications that utilise the peculiar behaviour of matter when it is formed into very small structures (below a few hundreds of nanometres; around 0.0000001m). At this scale, the classical laws of physics give way to quantum laws, often resulting in materials displaying very different properties to those they have in their bulk form.¹ Such changes include colour, conductivity, reactivity and physical strength,² amongst others.

Nanotechnology is considered to be so important because it bears all the signs of being a powerful general purpose technology (GPT), similar to electricity, the steam engine and the computer.³ GPT's are characterised as being applicable to many different sectors of industry, having large impacts on other technologies, and driving significant changes in economic productivity. Whilst extremely positive for productivity over the longer term, GPTs can cause significant disruption and require massive investments in infrastructure when they are first introduced.

Nanotechnology is not just a future vision - many nanotechnologies are already used in products on the market today.⁴ However the use of the word “nano” is not regulated, and many products are marketed as “nano” merely because they are small or new, even though the products themselves often do not use any nanotechnologies.⁵

Over the last decade nanotechnology has seen explosive growth worldwide in both advances and investment, similar to that which occurred with genetic technologies in the 1990s. This sudden appearance is due to many reasons, primarily because nanotechnology is the result of convergent technologies (see ICPDE report n. 01 on the NBIC, FCRI, July 2008). Its emergence required the prior development of an array of capabilities in many different fields.⁶ Key among them; advances in microscopy that have enabled individual atoms to be imaged, advances in scientific theory that enabled the peculiar behaviour of matter at the nano-scale to be explained, advances in synthesis with control over size, shape and assembly, and advances in manufacturing techniques driven by the semiconductor industry that allow nano-scale structures and particles to be easily produced.

Nanotechnology has practical applications in almost every area; medical nanotechnologies⁷ offer vastly improved treatments, implants and surgical devices; nano-materials offer stronger and lighter construction materials, corrosion resistant surfaces, even completely new materials integrating biologics with inorganics; nano-electronics offer ever smaller and more powerful computing, flexible video displays and circuitry woven into clothing; nano-particles offer improved cosmetics and catalysts; important applications also exist in energy, household goods, food, the environment, aerospace and the military.

In general, most forecasts describe three broad phases of nanotechnology development:⁸

- ▲ **Early stage (next 5 years):** *nanotechnology is at investigation phase and scientific knowledge is beginning to take shape in solid applications;*
- ▲ **Commercial development (5-10 years):** *during this period many different applications are expected to be developed and to begin to be produced on an industrial scale;*
- ▲ **Widespread use (10-15 years):** *nanotechnology will be consolidated as an industry and consumers will enjoy a wide range of products using nanotechnology. At this point it is anticipated that the worldwide market for nanotechnology enabled applications and products could exceed US\$1 trillion.*

The impact on industry will differ from sector to sector. For some industries, nanotechnologies will offer incremental improvements and these changes may well be easily absorbed within a normal program of continuous improvement. Other industries, however, may require extensive replacement of outdated equipment and infrastructure with potentially disruptive consequences.

It should be noted that nanotechnology is not always expensive to implement. Once methods of production are known and commercialised, they may involve simple upgrades or refinements of existing processes. Therefore some industries will progress naturally to using nanotechnologies without requiring major investments.

Impacts on the environment have the potential to be both positive and negative⁹. Many nanotechnologies will improve efficiencies (use less energy and materials) and reduce polluting by-products. Nanotechnologies may also be used to monitor the environment and correct problems such as oil spills and control disease outbreaks. However some nano-materials, in particular nano-particles, may prove to be toxic and difficult to contain, thereby posing risks to human and environmental health. The current lack of strong regulation and control in this area is a major cause of concern¹⁰ for the general public.

The impact on society is expected to be profound¹¹ with many facets of everyday life affected and significant quality of life improvements. There are however a number of serious social issues developing; some nanotechnologies such as sensors and robots may pose significant challenges to privacy rights, the potential inequalities from those with access to nanotechnologies and those without may give rise to tensions, nanotechnologies potentially increase the risk posed by malevolent individuals or terrorist organisations, and the unknown health risks to both workers, consumers and the environment is probably society's most pressing concern. Whilst important, it should be noted that these concerns are not unique to nanotechnology, as similar concerns exist for most new technologies.

The initial driver behind the global advance in nanotechnology was public funding and it still plays a major role. The EU leads the world in public investment, with the EC

and member states investing over US\$2 billion per year since 2005, followed by the US ~US\$1.7 billion, Japan ~US\$1 billion and the rest of the world combined ~US\$0.7 billion.⁸ This is reflected in scientific output, with the EU producing ~40% of peer reviewed scientific literature related to nanotechnology over the last decade.

However private investment in nanotechnology (which now exceeds global public funding) has been lagging in the EU compared to the rest of the world. Private investment in the US exceeds US\$2 billion and Japanese investment US\$1.7 billion, yet European industry is investing only US\$1 billion per annum. This lack of involvement by industry is reflected in the number of patents granted and products brought to market, with the US¹² and Japan clearly doing better than Europe, which produces only some 12% of nanotechnology products currently on the market.

Spain, like most other advanced countries, has seen tremendous growth this decade in nanotechnology related R&D. In the year 2000, fewer than 100 scientists nationwide were dedicated to nanotechnology, now that number is well over 1000 with many more scientists in diverse fields involving aspects of nanotechnology in their work.¹³

Nevertheless, Spain's investment in nanotechnology is well behind many other countries of similar, and even smaller size, both on a total and a per capita basis. Furthermore the general European problem with technology transfer appears to be even more acute in Spain.¹⁴

Within Spain, Catalonia has the largest number of nanotechnology groups after Madrid, with a dedicated Institute of Nanotechnology as well as a number of other institutes and research groups heavily involved in nanotechnology.

A large number of reports have been written in recent years on the various technological, industrial and social issues surrounding nanotechnology.^{15,16,17} Most favour strong action in public policy to invest in basic research while encouraging and stimulating technology transfer and the development of commercial applications; regulate health and safety issues, and develop international labelling and measurement standards; address workforce needs by establishing multi-disciplinary training and education schemes, supported by more general public education on nanotechnology.

In addition to these general objectives, regions such as Catalonia could also consider how best to focus limited resources. Other small regions and countries are attempting to create individual niches in technological and industrial capabilities in order to attain leadership in one or more sectors. Catalonia has significant existing strengths in certain industries and technologies, such as biosciences, that could be leveraged in this way.

INTRODUCTION

Nanotechnology refers to any technology that makes use of the peculiar properties of matter that begin to manifest when matter is structured at a scale below around 100nm (0.0000001 metres). Nano-effects are not new – they are widely present in nature, for example the carbon nano-particles in the soot of fires and the brilliant colours of butterfly wings produced by the nano-structured surface of their scales.

NANOTECHNOLOGY IN NATURE - Butterfly Wings

The colours of a butterfly are not formed by pigments, such as the colours of our eyes and the dyes used to colour our clothes, but rather by controlling and manipulating light via complex nano-structures.

Butterfly wings are covered by thousands of tiny scales, each of which are nano-structured in specific ways that cause only certain colours of light to be reflected at specific angles. These types of nano-structures are called photonic crystals and are found in many other natural examples, including the iridescent colours of a peacock's feathers and the mysterious colours of opal stones.

[Photograph of a blue morpho butterfly (*Morpho menelaus*) by Gregory Phillips, free available at http://commons.wikimedia.org/wiki/File:Blue_morpho_butterfly.jpg, under GNU license]



However what is new is our ability to observe, manipulate and control matter at the nano-scale and to do so in commercial quantities. A powerful convergence of new tools, capabilities and understandings are enabling scientists to not just observe, but also manipulate and form particles and structures at the nano-scale.

The science is also rapidly being commercialised into a vast array of new particles and devices with practical applications,¹⁸ ultra-sensitive sensors that can detect contaminants and pathogens, microscopic motion sensors for security applications, medicinal particles that can deliver drugs directly to tumours, surfaces that stick (or don't stick), integrated 'lab-on-a-chip' devices that can provide instant test results for at-home diagnostics. The list is endless.

The first wave of commercial products has already arrived, with over 807 on the

market worldwide,⁴ including everyday items such as toothpastes, cosmetics, tennis rackets and socks. To date these are fairly simple in both technology and function, yet with over 420 companies in 21 countries publicly proclaiming they are developing nano-technology related products the number and complexity of nanotechnologies is expected to explode, with forecasts^{8,15} of \$1 trillion in sales by 2015.

However along with benefits come dangers. Many of the nano-particles and nano-materials being developed do not exist in nature and their peculiar properties could pose serious health and environmental hazards.¹⁹ There is concern that if nano-industries are not properly regulated then the public may develop a distrust of the technology resulting in a similar backlash as occurred with genetic engineering technologies. The EC has acknowledged this concern and is acting to increase research and improve legislation in appropriate areas.

Also at issue for policy makers is how to assess in which domestic industries nano-technology is likely to be important for maintaining competitive advantage and to ensure that resources in R&D and technology transfer are adequately deployed to ensure that local industries do not become obsolete.²⁰ This is of particular concern in Europe, which seems to be lagging behind other regions in commercialising the results of its research.

The aim of this paper is to provide a broad overview of major recent developments in nano-technologies at both the research and commercialisation levels, highlight those issues which have been identified as being of concern to the public, and provide recommendations as to which public policies might be reviewed to address the needs of the public, industry and academia.

MAIN DISCUSSION

WHAT IS NANOTECHNOLOGY?

Definitions of nanotechnology vary, but the common theme is that it includes any technique that either manipulates matter at the nanometre scale or that makes use of the peculiar properties of matter that occur at that scale.²¹

The word “nano” itself originates from the Greek word meaning “dwarf”² and in scientific measurements means “one billionth”. Therefore 1 “nanometre” means 1 billionth of a metre. To give some perspective, the width of a human hair is around 80,000 nanometres. A DNA strand is about 2nm wide. A million nano-particles could fit on the dot of an ‘i’.

The fundamental contrast²² between nanotechnology and the older micro-technologies used in computer chips, is that the downsizing process has broken through a critical barrier; beyond it, the laws of classical Newtonian physics don’t always apply and different laws described by Quantum physics dominate.

Any material reduced to the nano-scale can therefore behave very differently than it does in its bulk form. For example, electrically insulating materials can become conducting, insoluble substances soluble, colours can change or become transparent.

Nanotechnologies come in many forms:²³

- ▲ **Nano-particles** are particles of any material that are smaller than around 100 nm. These often occur **naturally**, for example in the smoke from fires and the ash from volcanoes. They have been produced **accidentally** by human activities, for example in the exhaust of car engines, and they are now increasingly being manufactured **deliberately** (for example, nano-sized titanium dioxide particles in sun creams, to protect the skin from UV radiation).
- ▲ **Nano-tubs** are tubular structures, usually composed of carbon atoms, which have a diameter in the nanoscale, typically several nanometres across. They can exhibit extraordinary strength and unique electrical and thermal properties, making them potentially useful in many applications in electronics, optics and other fields of materials science, as well as potential uses in architectural fields.
- ▲ **Nano-electronics**²⁴ when defined by scientists, usually refers to electronic circuits and devices that make use of the special properties of matter at the nanometre scale (for example atom-sized transistors that can be switched with just one electron). Although most computer chips produced in the last few

years carry millions of transistors that are smaller than 100 nm (and therefore could strictly be called nanotechnology), because these functions in much the same way as their larger predecessors, they are not generally considered to be truly nanotech but rather just nano-sized versions of traditional micro-electronics.

However, because transistor sizes are now approaching the scale at which nano-effects come into play, they are reaching the physical limit of miniaturisation. The huge investment currently being made in nano-electronics is therefore aimed at developing the next generation technology (leading contenders include molecular electronics and optical switches) that will enable computing power and miniaturisation to keep progressing past the physical limit of current microelectronic technologies.

- ▲ **Nano-materials** són materials estàndards com ara metalls, plàstics i compostos que incorporen nanopartícules o nanosuperfícies. Inserir petites quantitats de nanopartícules a una substància pot alterar espectacularment les seves propietats i, per exemple, permetre de crear materials de construcció més lleugers i resistents. De la mateixa manera, l'aplicació de fines capes superficials de materials nanoestructurats pot modificar enormement les propietats de les superfícies i transformar els materials en resistents a les ratlladures, facilitar la seva neteja o fins i tot fer-los capaços de convertir l'energia solar en electricitat (materials fotovoltaics).
- ▲ **Nano-medicine** is the application of nanotechnology to medical applications. This could include the use of nano-sized devices such as sensors and implants, nano-structured coatings on surfaces (e.g. to avoid the body rejecting mechanical implants), or nano-sized particles to improve drug delivery.

Importantly, nanotechnologies potentially offer tools that will help in the development of theranostics, the ability to combine diagnosis and therapy. For example, several companies are developing nanoscale devices to be injected into the body that could identify a cancer and act immediately by releasing a drug directly at the cancer site.

- ▲ **Nano-robotics**²⁵ is the development of tiny machines, which could be used for medical applications (e.g. tiny robots to scrub your arteries free of cholesterol deposits), but could also be used for many other purposes, as environmental sensors to repair and clean machines and homes or even to construct other machines.
- Although working nano-robots are still very far from being developed, the concept is of concern to many people, as such machines could cause significant damage if designed maliciously or allowed to run out of control.
- ▲ **Nano-sensors** are nano-sized devices that measure physical, chemical or biological properties, and relay the information in a way which is useful for humans. For example they could be dispersed throughout a manufacturing

plant and report on any leaks of dangerous chemicals, or they could be used in public places to detect dangerous diseases, explosives or poisons. Commercial nano-sensors are at the early stages of development although it is envisaged that these will be available much sooner than nano-robots.

TOOLS EXAMPLE – Electron and Atomic Force Microscopes

Microscopes using light have been used for hundreds of years to enable scientists to study microscopic structures. However light based microscopes have a fundamental limit of about 1000 times magnification.

In the 1920s it was discovered that electrons travelling at high speed behave like light, and that furthermore magnetic and electric fields could be used as lenses to focus and direct them. Dr Ernst Ruska at the University of Berlin combined these characteristics and built the first Transmission Electron Microscope (TEM) in 1931. For this and subsequent work on the subject, he was awarded the Nobel Prize for Physics in 1986.

Recently electron microscopes have undergone dramatic improvements. Modern day electron microscopes can achieve magnifications up to 1 million times with a resolution of 0.1nm – powerful enough to see individual atoms.

Another form of microscopy called scanning probe microscopy was developed in 1981 by Gerd Binnig and Heinrich Rohrer (for which they also shared the 1986 Nobel Prize for Physics). Scanning probe microscopy uses a sensitive tip to directly interact with the surface of sample to build a 3-D image of the sample surface.

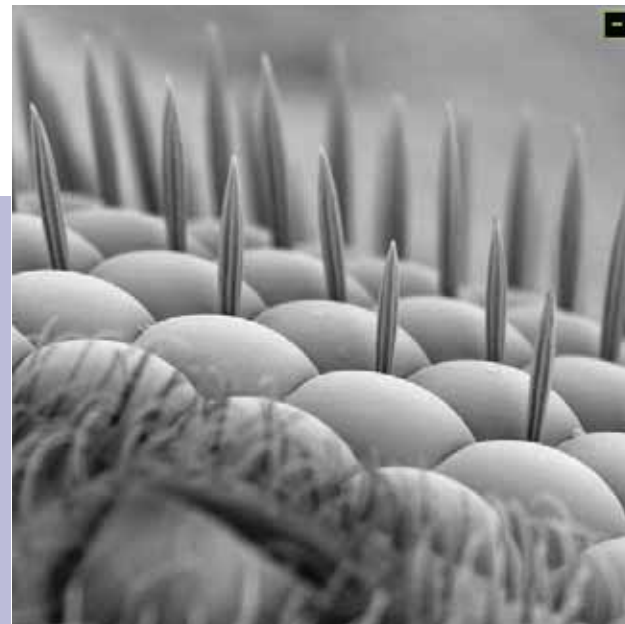
A number of different scanning probe systems have since been developed, including the Atomic Force Microscope (AFM) which has been particularly useful in the development of nanotechnologies due to its ability not only to measure surfaces but to also manipulate atoms and molecules on the surfaces of samples.

The AFM is significantly cheaper and able to operate in much less stringent environments than electron microscopes and is able to image almost any type of surface, including polymers, ceramics, composites, glass, and biological samples.

These tools enable scientists to push the boundaries of discovery and exploration, facilitating breakthroughs in pharmacology, biotechnology, forensics, pathology, materials science, semiconductor manufacturing and data storage.

[Photographies available at http://www.fei.com/Resources/image_gallery.aspx; http://www.fei.com/uploadedImages/Resources/image_gallery/images/others/fly_eye.jpg and <http://www.fei.com/resources/nanoscale-bug.aspx>. ©FEI Company.]

▲ **Nanotoxicology** is the study of the toxicity of nano-materials. Most concerns in regards to toxicity relate to nano-particles, although nano-structured surfaces and nano-medical devices also have potential to cause harm. Some nano-particles are potentially dangerous due to specific properties such as small size,



large reactive surface area or the difficulties in keeping them from spreading into the environment.

WHY IS NANOTECHNOLOGY IMPORTANT?

Nanotechnology is considered by many to be extremely important because it shows all the signs of developing into a General Purpose Technology (GPT).

“General Purpose Technology” is a term³ used by economists to describe great leaps of innovation that can affect entire economies, usually at a national and eventually global level. Past examples include the development of writing, steel, the steam engine, railroads, electricity, telecommunications and computers.

GPTs are characterized by:

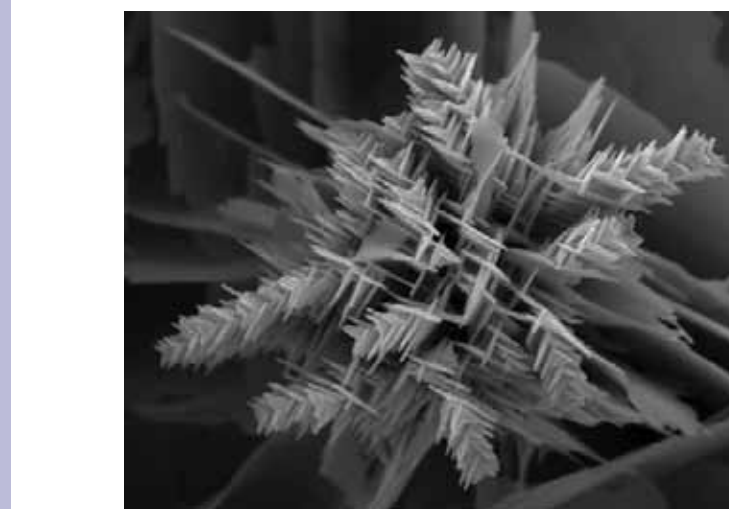
- ▲ **Pervasiveness:** they are used in many downstream sectors;
- ▲ **Technological dynamisms:** they increase the potential of an economy to support continuous innovation in industry and science, and
- ▲ **Innovational complementarities:** they provide improved capabilities in many other technical areas, thereby increasing the productivity of research and development in many sectors.

As a result of these impacts, GPTs have profound effects on the economy. Not all of these effects are good – although GPTs can lead over the longer term to huge increases in productivity and economic growth, in the shorter term they can create significant disruption.

Existing infrastructure, equipment and work skills can become outdated, meaning that companies close down, workers need retraining and governments are forced to make significant investments in upgrades. (A classic example is the introduction of the steam engine and railroads).

Sometimes the introduction of a GPT can create social concerns even before problems arise. When computer technology first started to become widespread there were fears that people would become redundant and computers would take their jobs. There was some truth to this, as many manual jobs became obsolete, so people were forced to retrain to become computer operators and programmers. However the feared negative impacts were largely not realised.

It is too early to say definitively whether nanotechnology will be a major GPT, but it shows all the early signs – it theoretically makes possible more efficient



manufacturing and communication, it impacts on virtually every major industry, from computers to textiles to medicine, and it facilitates scientists in furthering many other fields of knowledge by providing them with more powerful experimental tools.^{26,27}

– When is Nano not “Nano”?

Ever more consumer products are being branded with “nano” which to the average consumer conveys an image of new and/or small and/or high-tech. A classic example is Apple’s iPod Nano music player which has achieved worldwide success.

Yet in many instances, as with the iPod Nano, the product does not truly contain nanotechnology. At least in the iPod case it is true that the computer components inside do have features at the nano-scale, although these are no different to those found in your PC, and would not qualify as nano-technology according to the definitions given in this report.

This form of “false” advertising is of concern to many. Advocates of nanotechnology fear that if products marketed as nanotechnology under-perform or are found to adversely affect health or the environment, then nanotechnology as a whole will unjustly suffer.

Consumer groups are also concerned, fearing that companies will take advantage of the complexity of nanotechnology and mislead consumers into thinking a product has the features associated with nanotechnology when in fact it does not.

Below are two real examples where such situations have already occurred:

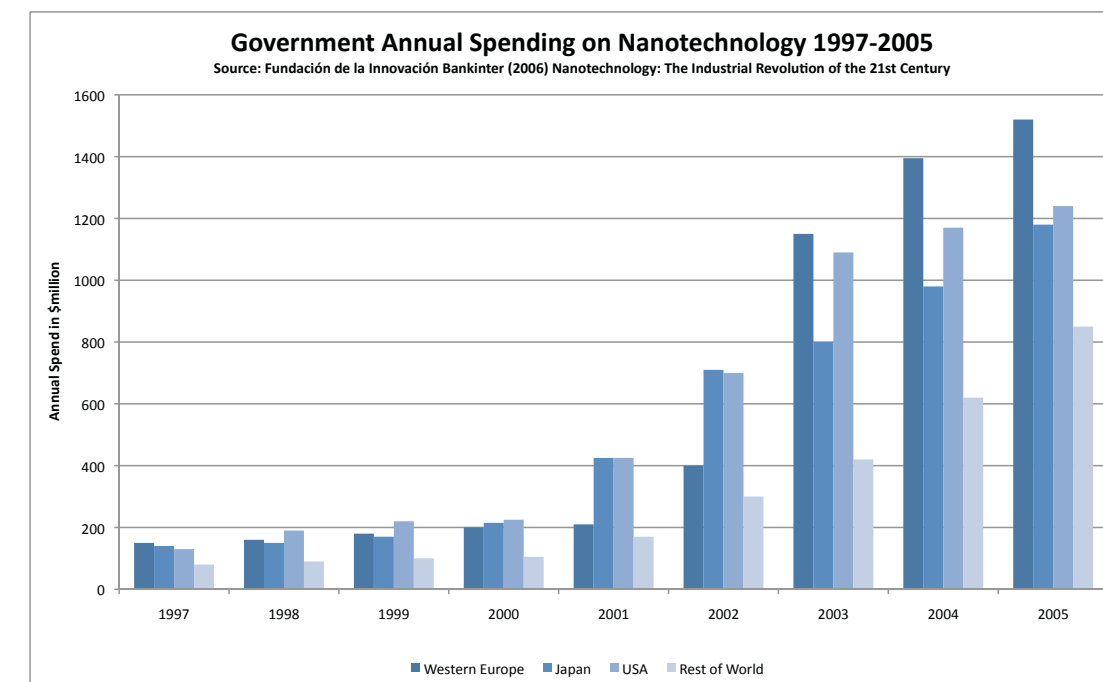
CASE 1: In Germany in March 2006 an incident relating to an aerosol sealant spray known as “Magic-Nano” led to approximately 100 people being hospitalised with severe respiratory conditions. However, a thorough investigation by the German Federal Institute for Risk Management (BfR) found that, despite the product’s name, the product did not actually contain nanoparticles, a finding confirmed by chemical analyses performed at two separate specialist chemical laboratories. The BfR found that the health problems were caused by inhalation of the aerosol spray.

CASE 2: Samsung’s Silver Nano washing machine is advertised as using silver nano-particles as an antibacterial agent. The machine produces silver ions – referred to as nanoparticles – by electrolysis which are released into the washing machine during the wash cycle. As the particles are then released into the water system, concerns have been raised over whether the silver ions could have a detrimental effect on the environment and on waste water treatment.

However the UK’s Health and Safety Executive (HSE), and the US’s Environmental Protection Agency (EPA) investigated and found that the silver particles were normal ions, as are found in all silver salts both natural and manmade. Since there are actually no nanotechnologies involved, there are no new risks beyond those ordinarily presented by silver ions.

[Source: Nanotechnology in Consumer Products, Nanoforum Report, European Commission, 2006; and Nanosciences and Nanotechnologies: A Review of Government’s Progress on its Policy Commitments, UK Council for Science & Technology, March 2007]

Because of this expectation, governments and private industry all over the world are spending billions on R&D in an effort to ensure they remain at the forefront of developments and are able to participate in the expected economic and social benefits.



WHY IS NANOTECHNOLOGY DEVELOPING SO QUICKLY?

Nanotechnology has been around a long time, although it wasn't known as such. Nano-particles, nano-structured surfaces, and nano-materials are widely found in nature and mankind has often inadvertently made use of their special properties. One of the earliest known uses of nano-materials dates back to the 4th century AD; the Lycurgus Cup from Rome is made of a special glass that changes colour when held up to the light. Modern investigation has shown that this special property is due to nano-sized particles of gold and silver which are contained within the glass.

ANCIENT NANOTECHNOLOGY - Lycurgus Cup

The Lycurgus cup was probably made in Rome in the 4th century AD.

This extraordinary cup is the only complete example of a very special type of glass, known as dichroic, which changes colour when held up to the light. The opaque green cup turns to a glowing translucent red when light is shone through it. The glass contains tiny amounts of nano-sized colloidal gold and silver, which give it these unusual optical properties.

The Lycurgus cup (left, normal view; right, view when held up to the light).

Photographs reprinted by permission from the British Museum.

http://www.britishmuseum.org/explore/highlights/highlight_objects/pe_mla/t/the_lycurgus_cup.aspx



It is also now known that the process developed by B.F Goodrich in 1885 of adding carbon black to tyres to make them black, and which incidentally also made them far more resistant to abrasion, was actually the inclusion of carbon nano-particles into the rubber matrix – one of mankind's first mass-produced composite nano-materials.

However the massive growth of interest in nano-scale science and engineering over the past decade is due to the conjunction of several factors:⁴

- ▲ **Technical advances** such as atomic force microscopy and electron microscopy have enabled scientists to both see and manipulate matter at the nano-scale;
- ▲ **Fabrication advances**, largely driven by the micro-electronics industry, and **synthesis advances**, in both organic and inorganic chemistry, have enabled commercial manufacturing of nano-scale devices;
- ▲ **Scientific advances** in physics and chemistry have led to understandings of how and why the properties of matter change so dramatically at the nano-scale;
- ▲ **Biological advances**, driven by the pharmaceutical and biochemical industries, have enabled nano-scale biological molecules to be bound to inorganic surfaces such as glass, metal and plastic, thereby enabling the linkage of biological, mechanical and electronic components;
- ▲ **Global co-operation in R&D** in many sectors has led to a critical mass of facilities and scientists engaged in developing nanotechnologies, such that advances are being made at a rapid pace, and
- ▲ **Increased government funding** in nanotechnology, in particular over the last 5 years, accompanied by a general belief by science and industry that nanotechnology will create a revolution similar to that created by semiconductor technology.

The current boom in nanotechnology is therefore the result of a convergence of technological advances that have come together over the past decade.

As new advances are made, for example in equipment to visualise and manipulate matter at the nano-scale, these in turn fuel further advances, leading to the snowball effect of technological and scientific advances and commercial applications that seems to be occurring.

A Short History of Nanotechnology

[Source: NANOTECNOLOGÍA, La revolución industrial del siglo XXI, Fundación de la Innovación Bankinter 2006; www.fundacioWikipedia: «Nanotechnology»]

The birth of the science of nanotechnology is famously credited to Richard Feynman, winner of the Nobel Prize for Physics, who in 1959 gave a keynote lecture entitled “There’s Plenty of Room at the Bottom”.

In his lecture, Feynmann examined the possible benefits for society of being able to catch atoms and molecules and put them down in given positions, and to manufacture artefacts with a precision of a few atoms.

Feynmann offered two prizes of \$1000 each: one for the first person capable of creating an electric motor in a 0.4 mm cube; the other for anyone capable of reducing the information on the page of a book by 25,000 times. The first prize was claimed the following year, but the second wasn’t claimed until 1985.

In honour of Feynman, since 1993 the Foresight Nanotech Institute offers the Feynman Prize in Nanotechnology to recognize significant achievements that contribute to the development of nanotechnology.

The term nanotechnology itself was coined by Norio Taniguchi¹, from the University of Tokyo in 1974, to distinguish between engineering at a micron level and engineering at a nano level. The term was made famous by Eric Drexler in his book *Engines of Creation*, published in 1986, which laid the theoretical foundation for much of today’s nanotechnology and articulated the amazing possibilities and dangers associated with engineering at the molecular scale.

Experimental nanotechnology began to accelerate in the 1980s with the development of new microscopes, such as the scanning tunnelling electron microscope and the atomic force microscope which could visualise and manipulate matter at the atomic scale.

In the 1990s, the amazing properties of carbon nanotubes, and other nano-particles were discovered, opening up the possibility of a much wider field of nanotechnology applications than had previously been envisaged.

The current wave of investment and acceleration of nanotechnology was kick-started in 1999 by then US President Bill Clinton who announced a National Nanotechnology Initiative. Similar initiatives were launched soon after by Europe and Japan and the growth of nanotechnology has been accelerating ever since.

WHAT WILL BE THE IMPACT OF NANOTECHNOLOGY?

Opinions differ widely on how fast the nanotechnology revolution may occur and to what extent it will impact on both local and global economies.

Timeline

In general, most analysts foresee three broad phases of development:⁶

- ▲ **Early stage (next 5 years):** *nanotechnology is at investigation phase and scientific knowledge is beginning to take shape in solid applications;*
- ▲ **Commercial development (5-10 years):** *during this period many different applications are expected to be developed and to begin to be produced on an industrial scale, and*
- ▲ **Widespread use (10-15 years):** *nanotechnology will be consolidated as an industry and consumers will enjoy a wide range of products using nanotechnology.*

The above estimates on timeframes vary quite significantly from industry to industry.

Medical applications will take much longer. Because new medical applications have very strict requirements with long clinical trials, medical nanotechnologies are expected to take several decades before they are in common use.

Industrial applications are already commercially available —the use of nano-materials in widespread commercial applications such as paints, adhesives and construction materials is already occurring.

APPLICATION EXAMPLE - Nanotechnology makes textile fibers dirt-repellent

Nano-particles give the surface of these textile fibers a structure with an effect similar to that of the lotus plant's leaves. From the leaves of this plant water and dirt just roll off. This effect makes the fibers water- and dirt-repellent. Tiny particles measuring less than 100 nanometers on the textile fibers produce a similar self-cleaning effect. These surfaces are coated with billions of these nano-particles so close together that a speck of dust wouldn't fit between them. Between a particle of dirt and the surface of the textile fibers, a layer of air is formed on which the impurities "hover" – and can simply be washed off with water. Even stubborn dirt is then easy to remove.

The nano-coating has so far been applied mainly to engineering textiles, such as fabrics for tents, awnings or sunshades. But materials used for work clothing and home textiles will also be benefiting from this new technology in future.

[©Press Photo BASF]

**Factors affecting the development of nanotechnology**

Asides from factors specific to particular applications, such as licensing of medical products, there are a number of general factors that will affect the development and spread of nanotechnology.

Capability factors:

The existence and availability of suitable tools to allow study at the nano-scale.
Suitable public and private infrastructure.

Coordination between research centres and business in technology transfer and commercialisation and educated and trained interdisciplinary workforces.

Financial factors:

Una bona identificació de les aplicacions pràctiques per a atreure inversions privades.
A reduction in the costs of processes and equipment.
Investment centred on specific projects rather than dispersed among different industries.
Availability of venture and other forms of start-up capital.

Government factors:

Government policy that encourages innovation and the development of nanotechnology.
Specific regulation for nanotechnology and its applications.
Coordination between countries/regions.

Social factors:

Public acceptance of nanotechnology, in particular as regards safety and privacy issues.
Confidence in regulators and regulatory processes.

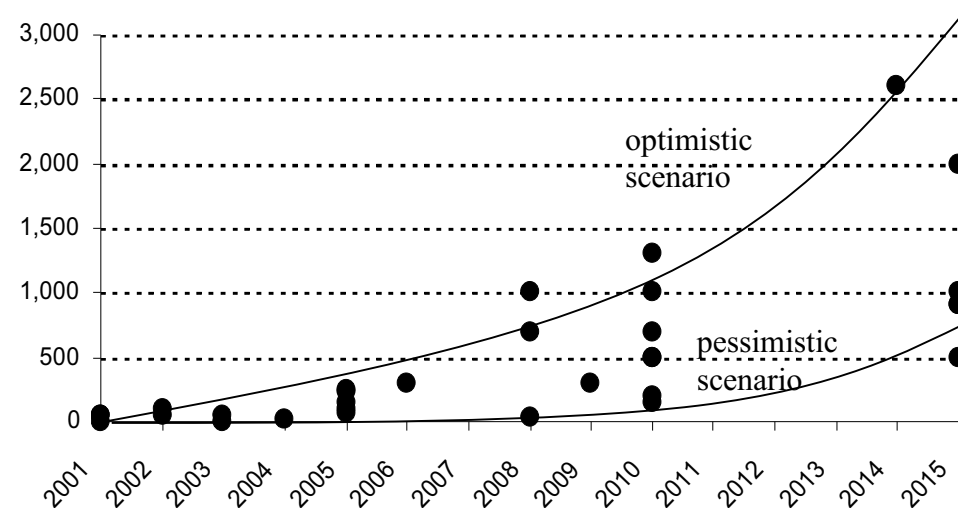
Serendipity:

Many new discoveries are anticipated for the near future, but as with all research, it is impossible to know beforehand what will, or will not be, discovered.

Size of the market

In recent years there have been numerous studies estimating the future sizes of different segments of the nanotechnology markets. These range from⁸ \$150 billion by 2010 (Mitsubishi Institute) to \$2.6 trillion by 2014 (Lux Research). One of the most well-known figures is that published by the US National Science Foundation of \$1 trillion by 2015.

[© Fundación de la Innovación Bankinter (2006). «Nanotecnología. La revolución industrial del siglo XXI» at <http://www.fundacionbankinter.org/3dissue/longes/nanotecnologia.pdf>]



Impact on industry

Nanotechnologies are expected to:

- ▲ **Improve existing technologies:** *glues that stick better, construction materials that are stronger and lighter, surfaces that clean easier or don't scratch;*
- ▲ **Enable entirely new applications:** *clothes made of materials that kill bacteria, sensors that detect contaminants and germs, drugs that release only in the tissues where they need to act, paints that can act as solar cells, and*
- ▲ **Improve efficiencies:** *new catalysts to reduce wastage in chemical processes, improved storage and efficiency of fuel cells, more powerful computing and communications technologies; coatings that last longer and need less cleaning.*

APPLICATION EXAMPLE - Nanocubes act as a storage medium for hydrogen

The desire to be mobile and yet not to be without communication and entertainment had led to ever smaller and lighter electronic devices. Whether it's laptops, cell phones or CD players, a key issue is how to power these portable devices. What batteries do today could in the future be done by mini fuel cells. Hydrogen could act as a source of energy provided that the problem of storage for its use in mobile devices can be solved. A possible storage medium for hydrogen would be nanocubes made of metal organic frameworks (MOFs), whose properties are currently being tested by BASF researchers. [© Press Photo BASF]



Impact on the environment

The environmental impact of nanotechnology is still largely unknown. It is expected that nanotechnologies will have both positive and negative effects.

Positive effects may derive from improved efficiencies in industrial processes, more efficient energy systems, better performing materials which need less repair and maintenance and enhanced protection of the environment through better sensors and filters for monitoring and controlling pollution and disease.

Negative effects may derive from the potential toxicity of nano-particles and nano-tubes, unintended side effects of manufacturing processes and materials, the misuse of nanotechnology for bioterrorism, and badly controlled nano-machines resulting in unintended damage.

Environmental benefits

[Sources: Geo Year Book 2007; Nanocap - Applications of Nanotechnology: Environment, November 2007]

Nanotechnologies are likely to have important positive environmental benefits in a number of ways:

Savings in raw materials: nano-materials that are stronger, more durable or otherwise more effective mean that less raw materials will be required in products ranging from buildings to machinery. Less raw materials in turn requires less mining, processing and transport leading to reduced environmental impacts throughout the production chain.

More efficient processes: nano-technologies are already providing improved catalysts for chemical reactions and energy transformations. Improved efficiencies imply reduced energy and raw materials requirements.

Improved Monitoring: nanotechnology enabled detection devices can be significantly less expensive and more sensitive than conventional ones. These can be used to monitor air, water and soil, detecting both contaminants and naturally occurring substances. Improved monitoring not only tracks pollution, but also enables farmers to improve crop management and better utilise fertilisers and pesticides.

Functional surfaces: nanotechnology surfaces with functional properties are already commercially available. These might be surfaces that are self cleaning (waters and oils don't stick) used for roofing, cars and walls, or clear glass and plastics that transmit less heat thereby reducing airconditioning needs of buildings, surfaces that don't scratch, etc. Cleaning, restoring and repairing surfaces consume huge amounts of resources, so any technology that leads to large savings in this area will have huge benefits to the environment.

Remediation of pollution: some nano-structures show excellent promise for use in filtration and catalyst systems, to remove contaminants from air, soil and water. These can be employed at source, for example outlets of factories or vehicles, or to help clean up polluted environments such as oil spills and contaminated land.

Energy storage and production: nanotechnologies are expected to significantly improve solar cells, fuel cells, batteries and other energy technologies. All these combined are likely to result in significant improvements in energy production, storage and efficient utilisation, in turn reducing greenhouse gas emissions and environmental damage.

The main immediate environmental concern is focussed on nano-particles²⁸ which are not embedded in a fixed matrix, as these are an early application that in some cases are already in mass production, and they have the theoretical potential to cause a lot of harm to both human health and the environment generally.

Impact on society

Because nanotechnologies are expected to be very widespread, affecting many industrial sectors and consumer products, it is anticipated that significant social, economic, workforce, educational, ethical and legal issues will arise.²⁹

Research has shown³⁰ that the primary concern of society with nanotechnology in general is the impact on human health and the environment. Beyond these broad concerns, issues tend to be specific to particular applications. Often these issues exist already and are not unique to nanotechnology, but may become more important as nanotechnology makes the application more accessible and widespread.

For example, initial medical applications of nanotechnology are likely to be very expensive, leading to a health divide based on wealth, between those who can afford a nanotech cure for their cancer and those who cannot. Whilst this is an important social issue, it is not unique to nanotechnology; the same is true of most new forms of medical treatment. (See Appendix “Ethical Legal and Social Aspects”).

Concerns have also been raised at futuristic scenarios, where runaway hordes of nano-robots chew up the earth and turn it into ‘grey-goo’, or malicious nano-bugs are used to infect people turning them into hostages of those who control the bugs. While these and other vivid scenarios are hypothetically possible, current technology is very far from having these capabilities and concern by mainstream science is focussed on the more immediate threats.

As discussed earlier, currently the key perceived threat is the unknown (and at the moment unmeasurable) toxicity of nano-particles and nano-tubes. Because nano-particles are relatively easy to produce (compared to more complex nanotechnologies) and have widespread applications, they are already being used in commercial applications and are expected to be used in many more. Many of these applications involve the nano-particles and nano-tubes being embedded in a fixed matrix (such as glass, plastics or construction materials) and so are not of particular concern —the main risk stems from free nano-particles and nano-tubes.

Examples of current nano-particle use include zinc oxide or titanium dioxide nano-particles in sunscreens and cosmetics to provide UV protection whilst allowing the cream to be transparent, carbon black particles in tyres to improve resistance to wear (used since the 1920s), silicon dioxide (glass) nano-particles in scratch resistant surfaces to improve durability, and even gold nano-particles that change colour for use in sensing devices such as home pregnancy tests.

APPLICATION EXAMPLE - Zinc oxide nano-particles in sunscreen

Z-COTE ® is a special zinc oxide which, used in suncreams, offers protection against sunburn by filtering against harmful UVA and UVB radiation.

The fine particles of zinc oxide function as physical UV filters - UV radiation is not only reflected, but also dispersed and absorbed by them. Since these particles are white, they can cause an undesired whitening effect on the skin at high concentrations.

This is prevented by reducing the size of the pigment particles to about 200 nanometers – which makes them transparent on the skin. Physical UV filters are used mainly in sunscreens with higher sun protection factors above 25. They are also suitable for the sensitive skin of children and people with allergies.

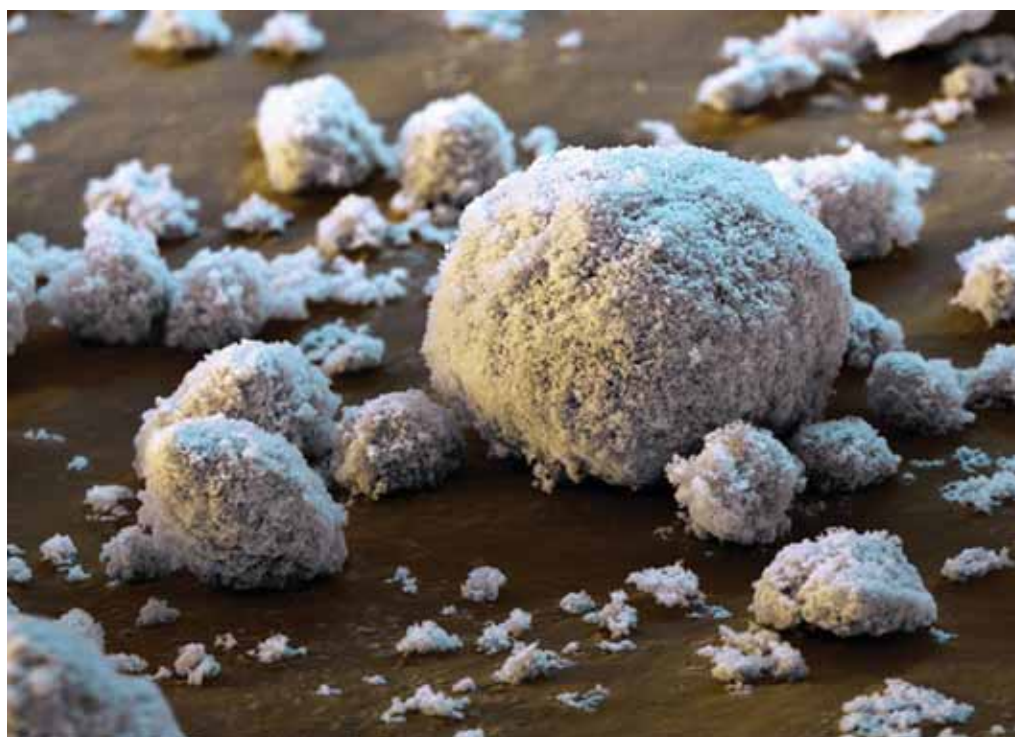
In some of these cases, such as tyres or construction materials, where the nano-particles are contained within a solid there is less concern of direct impacts on human health and more concern of the long term environmental impact, as the encasing solid decays and releases the nano-particles into the environment.

In others, such as cosmetics, there is concern at the unknown direct health impact of nano-particles, both because they penetrate further into the skin than traditional, larger sized ingredients, and because their unique chemical properties may react with the body in unforeseen ways. Of especially high concern are those nano-particles that are likely to become airborne and thus inhaled into the lungs. There is some preliminary evidence³¹ showing that carbon nano-tubes above a certain length can act as irritating fibres, showing some similarities to asbestos.

However not all nano-particle production is deliberate; car exhausts have been pumping significant quantities of nano-particles into the air for a century. To date, besides from the general negative impacts of pollution, no specific ill effects have been directly attributed to the nano-scale nature of these particles.

Nanotechnology may have a positive role to play in this regard, as better understanding of the nature of nano-particles and development of other nano-materials is expected to lead to new technologies that could significantly reduce air pollution.

In much the same way that asbestos, GM-foods and other new technologies or products have sometimes been rapidly introduced only to be followed by disastrous consequences or social backlash and rejection, there are fears that allowing nanotechnologies to be introduced without due care and regulation could lead to a similar reaction.



[© Press Photo BASF]

One of the difficulties faced by those wanting to implement more stringent regulation and testing is that nanotechnologies are so varied, with such differing risk/benefit profiles, is that it is neither feasible nor desirable to enact widespread, general regulations. For example, requiring that no device emit man-made nano-particles into the atmosphere would make all combustion engines (such as cars and planes) illegal. On the other hand, there are so many nanotechnology applications either on the market or under development, that it is also not feasible to examine each on a case by case basis.

Thus the current challenge faced by society, governments and industry in attempting to minimise potential risks while not stifling technological development. A recent EU³⁷ highlights that “mechanisms to address these concerns and to sort out what is real from what is imaginary are needed. Promising strategies that have been implemented in the EC are scientific cafes and consensus conferences. In these venues, scientists meet with citizen groups to discuss implications of new scientific discoveries. Such meetings have the potential to build communication and trust between the public, policymakers, the media, and the technical community.”

Job creation, education & training

In terms of employment, it is claimed³² that nanotechnology development is likely to require an additional two to ten million workers across the world by 2014. If Europe maintains a leading edge in nanotechnology it can expect that many of these jobs will be created in Europe, especially in start-up companies and SMEs.

Asides from direct employment, the expected diversity of nanotechnology applications is likely to result in their incorporation into many facets of life, thereby improving and enabling many other industries.

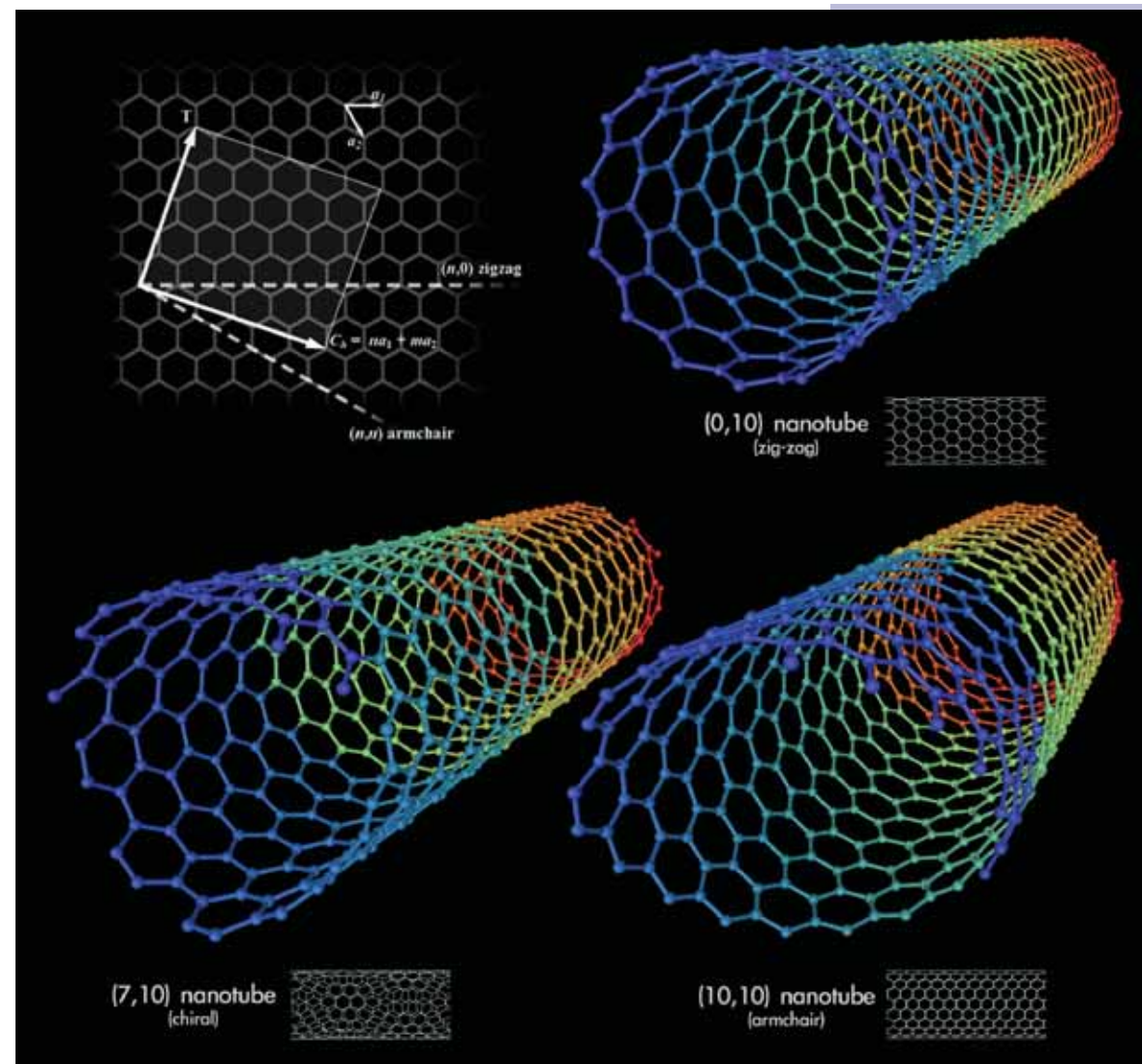
An analogy can be made with electricity. Although only a relatively small number of people are directly employed in the generation and distribution of electricity, the impact of electricity on the wider workforce is immense. Virtually no-one in the western world would perform their work without at some point utilising electricity in some way, even if it is just to turn on a light.

In much the same manner as electricity enables other processes, it is expected that nanotechnologies will also improve existing, and enable many new, processes and activities.

The extent to which this will occur will depend very much on the speed with which nanotechnology applications are brought to market and the extent to which individual countries have adequately trained and educated workforces that can adapt and incorporate the new technologies.³³

Education and training has been identified as a key requirement by virtually all major nanotechnology initiatives.

The US National Nanotechnology Strategic Plan¹⁶ has as the 3rd of 4 major goals: “to develop and sustain educational resources, a skilled workforce, and the supporting tools and infrastructure to advance nanotechnology ... educational programs and resources are required to produce the next generation of nanotechnologists, that I, the researchers, inventors, engineers and technicians who drive discovery, innovation, industry and manufacturing”.



Carbon nanotubs

Carbon nanotubes are rolled up sheets of carbon atoms. The tubes come in many forms, different lengths, widths and configurations. They can have closed or open ends, curves and even multiple concentric walls (tubes within tubes), known as multi-walled nanotubes.

[Photograph by Michael Ströck and free available at http://commons.wikimedia.org/wiki/File:Types_of_Carbon_Nanotubes.png, under GNU license.]

Carbon nanotubes are of particular interest to both scientists and industry for a number of reasons.

Carbon nanotubes are the strongest and stiffest materials on earth, and have already been used to produce stronger and lighter composite materials for aircraft and sporting equipment.

Multi-walled nanotubes exhibit a striking telescoping property whereby an inner nanotube core may slide, almost without friction, within its outer nanotube shell thus creating an atomically perfect linear or rotational bearing. Already this property has been utilized to create the world's smallest rotational motor.

The structure of a nanotube strongly affects its electrical properties which can range from semiconductor to metallic. Theoretically, some carbon nanotubes could carry currents 1000 times denser than those carried by traditional wires such as copper.

Are carbon nanotubes safe?

The answer to this is still unknown. Studies are very difficult as each type of carbon nanotube is unique and behaves like a different substance. Parameters such as structure, size distribution, surface area, surface chemistry, surface charge, and agglomeration state as well as purity of the samples, have considerable impact on the reactivity of carbon nanotubes.

However, available data clearly show that, under some conditions, nanotubes can enter cells and suggests that if raw materials reach the organs they can induce harmful effects as inflammatory and fibrotic reactions. There are some fears that carbon nanotubes could behave like asbestos fibres.

The EU's Strategic Plan for Nanotechnology¹ includes a section on human resources: "The Commission calls upon Member States to contribute to:

(a) *identifying the educational needs of nanotechnology and provide examples of best practice and/or results from pilot studies;*

(b) *encouraging the definition and implementation of new courses and curricula, teacher training and educational material for promoting interdisciplinary approaches to nanotechnology both at school and graduate level;*

(c) *integrate complementary skills into post-graduate and life-long training, e.g. entrepreneurship, health and safety issues at work, patenting, spin-off mechanisms, communication, etc."*

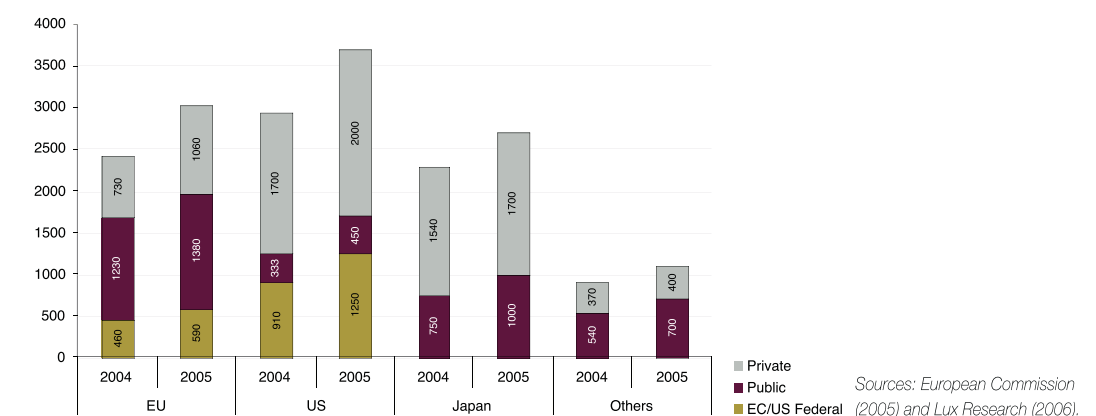
The German Innovation Initiative for Nanotechnology³⁴ has as one of its key goals "Promoting the young and developing qualifications ... One of the most important factors that goes into shaping a region's economic development and thus the creation of a nanotechnology-driven industry in Germany is not only the presence of a capable scientific and economic community but also the availability of qualified workers on all levels. If the increase sought in the number of self-employed people and the quick diffusion of technologies wanted are to be achieved, then a correspondingly qualified workforce is needed. Education is thus the key to the future nanotechnology job market".

CURRENT INVESTMENT IN NANOTECHNOLOGY

The technological development of the applications described in this document and the changes to existing industrial infrastructure necessary to bring these applications into widespread use will require large-scale investments. Those countries that fail to make appropriate investments risk having their industrial capabilities being made redundant and losing significant economic productivity.

To date²¹ it has been public funding that has enabled the early take-off of nanotechnology but the private sector is now beginning to invest heavily too, playing an increasingly important role. The current position varies from region to region, however: in America and Asia, the business sector already contributes more than government, but in Europe private sector investment lags behind. In Europe, only 33% of the total funding comes from private sources while in the United States, private sources provide 54% and in Japan they account for over 60%. In other countries (mainly emerging Asian countries) the share is around 36%.

This is of particular concern to European policy makers, as the technology transfer from the scientific sector to the industrial sector will largely depend on how quickly existing firms, especially SMEs, invest in both equipment and training to commercialise new nanotechnologies. Therefore although the European scientific sector is performing well, early signs are that private industry is not responding as fast as in other parts of the world.



[Source: Geo Yearbook 2007: «Emerging Challenges – Nanotechnology & the Environment»]

The European Union in its Framework Program 7 budget has allocated 3.5 billion euros into nanotechnology research between 2007 and 2013 (ie about 0.5 billion euros per annum), in addition to the private sector investment and national research budgets of European member states. In comparison, the US federal government alone currently spends over US\$1 billion (0.7 billion euros) per annum on nanotechnology research.

Within Europe, research in nanotechnology is concentrated mainly in Germany (almost half of all EU research institutes active in nanotechnology are located there) with the

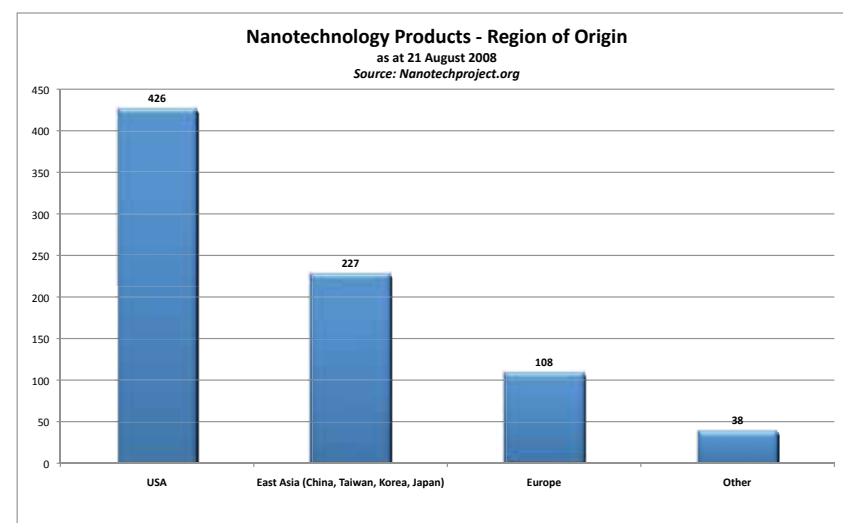
other major players being France and the UK (each representing about 8% of active institutes) followed then by western central and northern member states.

A sometimes useful measure of technology transfer is patenting activity. Patents reflect the intent of scientists to transfer scientific results into technologically based commercial applications and therefore the number of patents filed is an indicator of both the success of research and extent to which the inventions are being transferred to the industrial sector. The European Patent Office (EPO) has developed a methodology in order to identify and classify nanotechnology patents and this has enabled some analysis of worldwide and European trends in patenting activity.

The largest rate of commercialisation of nanotechnologies is occurring in the nano-electronics and nano-materials sectors, for reasons described earlier (see “Timeline” page 31) these areas are expected to drive the first wave of commercial applications.

If one looks at the regional breakdown of patenting activity, it is clear that Europe is lagging far behind the US and Asia.

And it seems that the lower level of patenting correlates with a lower level of commercial activity, with very few of the currently available nanotechnology products being manufactured in Europe.



Inventory of nanotechnology-based consumer products by region of origin [Source: www.nanotechproject.org].

Yet this is not due to a lack of suitable quality research in Europe; on the contrary, Europe accounts for around 40% of total published scientific output in nanotechnology. The lack of commercial exploitation of these research results is of high concern and the EC is placing increasing focus on developing mechanisms to encourage private industry, in particular SMEs, to collaborate with research institutes and invest in industrial-level R&D.

SAFETY & REGULATION OF NANOTECHNOLOGY

Safety in regards to nanotechnology has many aspects; safety in the laboratory, safety in the workplace, safety for consumers and safety for the environment.

The broad scope and variety of nanotechnologies, combined with their rapid rate of advancement and commercialisation, is creating concern in many segments of society that safety issues are being ignored at the expense of commercial gain.

EU legislation

The EC and various other public bodies within Europe, as well as equivalent bodies in the US and other countries, have issued various statements of policy and intent in regards to safe development of nanotechnologies.³⁵ Most of these are fairly similar in their approach,³⁷ therefore although the discussion below is limited to EU policies it should be taken as generally representative.

The EC has issued two key communications in recent years that define its policy in regards to health and safety: ***Towards a European Strategy for Nanotechnology (May 2004)***² and ***Regulatory Aspects of Nanomaterials (June 2008)***.³⁸

The 2004 communication outlined the key principles by which the EU's scientific and commercial communities should develop nanotechnologies:

Nanotechnology must be developed in a safe and responsible manner. Ethical principles must be adhered to and potential health, safety or environmental risks scientifically studied, also in order to prepare for possible regulation. Societal impacts need to be examined and taken into account. Dialogue with the public is essential to focus attention on issues of real concern rather than “science fiction” scenarios.

The communication gave some further detail (see Appendix “Extracts on Health and Safety from EC 2004 Communication”), however did little to give specific details on how these objectives should be achieved. This lack was identified early on and led the Commission to undertake a regulatory review, the results of which have just been published in June 2008.

The review concluded that “current legislation covers to a large extent risks in relation to nanomaterials and that risks can be dealt with under the current legislative framework. However, current legislation may have to be modified in the light of new information becoming available, for example as regards thresholds used in some legislation.”

The need for improved information is highlighted repeatedly : *“knowledge on essential questions such as characterisation of nanomaterials, their hazards, exposure, risk assessment and risk management should be improved ... knowledge becomes the critical factor for implementation and, eventually, legislation”* and therefore *“Authorities and Agencies in charge of implementing legislation should continue to carefully monitor the market, and use Community market intervention mechanisms in case risks are identified for products already on the market.”*

In order to assist this process of monitoring new products, the review identified that the relevant legislation can be grouped under four categories: **chemicals, worker protection, products and environmental protection**, and that when all are applied simultaneously the result is an acceptable level of protection of public health and safety. (See Appendix “EU safety legislation applied to nanotechnology”).

Public concern

Despite the fairly positive view of existing legislation by the EC, there is significant concern by worker and consumer groups that the existing legislation and the manner in which is implemented does not provide adequate safety regulation.

NanoCap (Nanotechnology Capacity Building NGOs) is a European project that was established to deepen the understanding of environmental, occupational health and safety risks and ethical aspects of nanotechnology. It established a consortium of 5 environmental NGOs, 5 trade unions and 5 universities that are holding a series of focused working conferences to prepare a portfolio on ethical issues and a position concerning “responsible nanotechnology”. The project is funded by the European Commission, from the FP6 Science and Society programme and runs from September 2006 until September 2009.

As an interim result of this process, the European Trade Union Confederation (ETUC) recently adopted a **Resolution on Nanotechnologies and Nanomaterials**³² in June 2008.

In the resolution the ETUC is generally supportive of nanotechnology *“the ETUC is convinced that nanotechnologies and manufactured nanomaterials might have considerable development and application potential. These technological advances and the new jobs they might bring may address peoples’ needs, help make European industry more competitive and contribute to the achievement of the sustainable development goals set out in the Lisbon Strategy.”*

However they note that significant uncertainties exist and that *“preventive action must be taken where uncertainty prevails. This means the precautionary principle must be applied. This is the essential prerequisite for the responsible development of*

nanotechnologies and for helping ensure society’s acceptance of nanomaterials.”

Precautionary principle

The precautionary principle has been defined in various ways. Two often quoted definitions are:

1. *When an activity raises threats of harm to human health or the environment, precautionary measures should be taken even if some cause and effect relationships are not fully established scientifically.*

In this context the proponent of an activity, rather than the public, should bear the burden of proof. The process of applying the precautionary principle must be open, informed and democratic and must include potentially affected parties. It must also involve an examination of the full range of alternatives, including no action.

Consensus statement by the Wingspread conference of treaty negotiators, activists, scholars and scientists from the United States, Canada and Europe, January 1998.

2. *Where, following an assessment of available scientific information, there are reasonable grounds for concern for the possibility of adverse effects but scientific uncertainty persists, provisional risk management measures based on a broad cost/benefit analysis whereby priority will be given to human health and the environment, necessary to ensure the chosen high level of protection in the Community and proportionate to this level of protection, may be adopted, pending further scientific information for a more comprehensive risk assessment, without having to wait until the reality and seriousness of those adverse effects become fully apparent evidents.*

Fisher, Elizabeth, Judith Jones i Rene von Schomberg (ed.). *Implementing the Precautionary Principle: Perspectives and Prospects*, Cheltenham, United Kingdom, and Northampton, USA: Edward Elgar (2006)

On 2 February 2000, the European Commission issued a Communication on the precautionary principle (COM(2000) 1) in which it adopted a procedure for its application. Since then the principle has come to inform much EU policy, including environmental policy, food law, consumer protection, trade and research, and technological development.

The ETUC resolution welcomes the EC’s acceptance of the precautionary principle in its 2004 and subsequent communications, but notes some significant deficiencies which it believes require immediate attention:

Funding for R&D on safety: *where investment in R&D is concerned, we see and note a gross imbalance between budgets for the development of commercial applications of nanotechnology and those for research into their potential impacts on human health and the environment. The ETUC calls for at least 15% of national and European public research budgets for nanotechnology and the nanosciences to be earmarked for health and environmental aspects and to require all*

research projects to include health and safety aspects as a compulsory part of their reportings.

Standardisation of terminology: a standardised terminology for nanomaterials is urgently needed to prepare meaningful regulatory programmes. In particular, ETUC calls on the Commission to adopt a definition of nanomaterials which is not restricted to objects below 100 nanometers in one or more dimensions. This is important to avoid many nanomaterials already on the market to be left out of the scope of future legislations.

No proof, no market: the ETUC finds it unacceptable that products should now be manufactured without their potential effects on human health and the environment being known unless a precautionary approach has been applied and made transparent to the workers. In particular, ETUC considers that manufacturers of nano-based products should be obliged to determine whether insoluble or biopersistent nanomaterials can be released from them at all stages of their life cycle. In the absence of sufficient data to prove that those released nanomaterials are harmless to human health and the environment, marketing should not be permitted.

Amend REACH chemical regulations: nanomaterials may indeed evade the REACH registration requirements ... the ETUC demands that different thresholds and/or units (e.g. surface area per volume) are used for registration of nanomaterials under REACH.

Improve training and safety in the workplace: there is a great need for training, education and research in order to allow health and safety specialists (e.g. labour inspectors, preventive services, occupational hygienists, company physicians) preventing known and potential exposures to nanomaterials ... The ETUC calls on the Commission to amend Chemical Agents Directive 98/24/EC which it believes does not afford adequate protection to workers ... employers must be required to implement appropriate risk reduction measures, not only when known dangerous substances are present in the workplace, but also when the dangers of substances used are still unknown.

Labelling: the ETUC believes that consumers also have the right to know what is in a product... the ETUC wants all consumer products containing manufactured nanoparticles which could be released under reasonable and foreseeable conditions of use or disposal to be labelled. In addition, as part of the precautionary approach, ETUC calls on Member state authorities to set up a national register on the production, import and use of nanomaterials and nano-based products.

In response to these and other similar calls for precautionary action, the EU has initiated a public consultation³⁹ with Member States and other stakeholders in order to increase knowledge and awareness about the potential of nanotechnologies and to continue to ensure an adequate protection of nature, environment and health.

Safety in the workplace

In June 2008 the European Trade Union Conference issued a **Resolution on Nanomaterials and Nanotechnologies** supporting the development of nanotechnologies but calling for preventive action to be taken where uncertainty prevails in regards to safety issues.

They call for the precautionary principle to be applied, such that workplaces treat nanotechnologies as hazardous until proved safe, rather than assuming they are safe until proved hazardous as is often done with new technologies.

The concern is that neither workers nor consumers should be exposed to unknown risks, as unfortunately happened with asbestos, which continued to be used for decades even after there was strong evidence of its toxicity.

Currently there are no requirements for workplaces to apply such principles, however some companies heavily involved in nanotechnology have voluntarily implemented a precautionary philosophy.

For example BASF, the chemical company that employs over 95,000 people worldwide, has implemented a **Nanotechnology Code of Conduct** and a **Guide to Safe Manufacture and for Activities Involving Nanoparticles in the Workplace**. BASF's Code of Conduct states:

The protection of human life and the environment is a fundamental principle for our company.

We identify sources of risk for our employees in our laboratories, production plants, packing facilities and storage facilities and eliminate these using the appropriate measures. In the event of any health and environmental hazards arising as a result of our operations, we take immediate action.

We are actively involved in the ongoing development of a scientifically based database for the assessment of potential risks as well as in improving and refining product-based testing and assessment methods. In addition, we actively debate the opportunities and risks of nanotechnology with partners from all areas of society.

Wherever existing legislation and guidelines have not yet taken developments in nanotechnology into account, BASF contributes constructively to drawing up legislation. Our goal is to establish risk-appropriate, solid standards and to support relevant legislation.

BASF only markets products if their safety and environmental impact can be guaranteed on the basis of all available scientific information and technology. We provide our customers and logistics partners with information about the safe transportation, storage, safe use, processing and disposal of our products. Economic considerations do not take priority over safety and health issues and environmental protection.

PRODUCING NANOTECHNOLOGY

In order for the vast array of potential nanotechnology applications to become widely available, industry will need to develop significant nano-production capabilities. For some industries this may involve fairly simple and progressive upgrades of existing systems, but for others it may require complete replacements of existing infrastructures with costs in the hundreds of millions of euros.

Light Up The World

Light Up The World (LUTW, www.lutw.org) is an international humanitarian organization dedicated to illuminating the lives of the world's poor. It is the first organization to utilize solid-state lighting technologies to bring affordable, safe, healthy, efficient, and environmentally responsible lighting to people currently without access to proper lighting.

Els avenços en nanotecnologia estan millorant considerablement el rendiment i l'eficiència. eDevelopments in nanotechnology are greatly improving the performance and energy efficiency of White Light Emitting Diodes (WLED). This is enabling the commercial production of ultra-efficient, durable and near permanent lights many times more efficient than normal light bulbs and which can be run off low voltages that are not dangerous. When coupled with renewable energy sources such as solar cells (which are also being improved with nanotechnology), much needed lighting can be provided to the world's poor, especially in ecologically sensitive and remote rural areas.

Since many of these people currently use kerosene lamps or other combustible fuels to provide light, the new technology also has significant environmental benefits, reducing smoke pollution in houses and greenhouse gas emissions.

[© 2007 Light Up The World.]

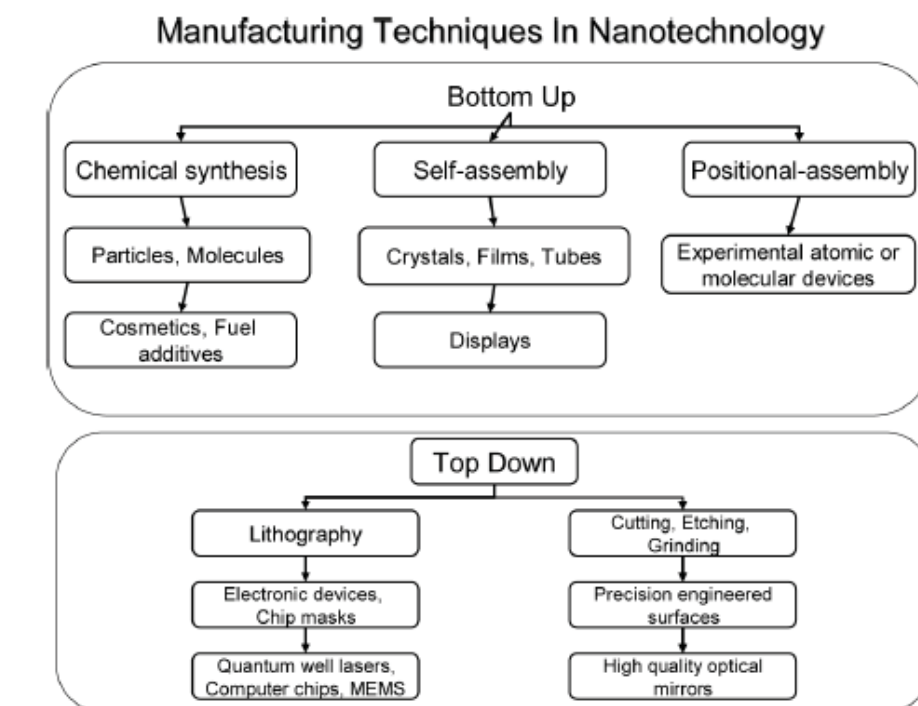


Top-down vs bottom-up

Most manufacturing at the nano-scale proceeds by one of two main routes:

“Top-down” starts from larger materials and structures and employs cutting or etching techniques to miniaturise the features until the required nano-structures are achieved. This can be compared to sculpting rock, where a large block is gradually chipped away until the required shape and detail is achieved.

“Bottom-up” starts with basic building blocks such as small molecules or even atoms and assembles them into the required structure. This can be compared to a LEGO set, where a number of basic building blocks can be assembled in many different ways to produce structures of the required size and complexity.



[Source: Tolfree, David. Commercialising Nanotechnology concepts–products–markets, Int. J. Nanomanufacturing, vol. 1, n. 1, 2006. © Inderscience Enterprises Limited.]

Currently the top-down approach predominates, mainly because of the huge existing infrastructure in the microelectronics industry which utilises top-down etching approaches to create electronic features on the surface of silicon wafers. However it is expected that in the future bottom-up approaches will become increasingly more important, as they theoretically provide for far more flexibility and purity of product.

Instrumentation & quality control

One of the biggest challenges currently impeding the development of industrial nanotechnology manufacturing techniques is the need for new tools and instruments to provide adequate process and quality control.

For example, it is fairly easy to produce nano-particles by starting with a large block of raw material and grinding it into a finer and finer powder until the particles are nano-sized. The problem with such a technique is that it does not produce a uniform size of particle: the resulting powder can contain a huge range of sizes and shapes. Simple and effective classification techniques to separate the particles into groups of uniform size and shape are required, however the technology to undertake such separations is still in early development.

If one considers more complex structures, such as nano-scale machinery or nano-sensors, the quality assurance challenge becomes much more difficult.

Imaging technologies, such as scanning and tunnelling electron microscopes, have progressed dramatically over the last decades to the extent where photographs at molecular and even atomic detail are now fairly commonplace.⁴⁰ The ability to directly observe matter at this level is one of the main reasons nanotechnology is currently experience such dramatic advancement.

However these imaging technologies are still very expensive and require careful control in laboratory conditions to produce good images. It will take significant further improvements before such technology is available for industrial manufacturing lines to provide good tools for quality control.

WHAT ROLE FOR GOVERNMENTS?

Given that nanotechnology is happening and that its impact on industry and society will be significant, the question therefore arises as to what extent governments should become involved in guiding, stimulating and regulating its development?

This question is further complicated by the broad and varied nature of nanotechnologies, each of which may require different approaches. Nevertheless a broad consensus seems to have emerged in recent literature of three key areas that require public intervention:

1. government funding of R&D to stimulate development and commercialisation,
2. government regulation in regards to health and environmental impacts to enforce the precautionary principle, and
3. government support of education and social dialogue, both in regards of workforce training and general education and public dialogue regarding the impacts of nanotechnology, with particular focus on safety and privacy concerns.

EU level

The EU has formally stated its public policy intentions in regards to nanotechnology: *“Nanotechnology provides important potential for boosting quality of life and industrial competitiveness in Europe. Its development and use should not be delayed, unbalanced or left to chance. The European Commission (EC) plays two important roles in the development of nanosciences and nanotechnologies (N&N); as policy maker and as funding body for research and innovation¹⁷”*.

In regards to policies its main actions to date have been the release of Communications, in particular:

- ▲ *Towards a European Strategy for nanotechnology (May 2004)¹*
- ▲ *Nanotechnology Action Plan for Europe 2005 – 2009 (June 2005)⁴¹*
- ▲ *Action Plan Implementation Report 2005 – 2007 (September 2007)¹⁷*
- ▲ *Regulatory Aspects of Nanomaterials (June 2008)³⁸*

These documents discuss the EC's view on the relative importance of different nanotechnology applications and capabilities, and thereby provide guidance through the relative allocation of funding for R&D in the different areas. Although most of the funding is directed at technical projects, some funds have been set aside for social dialogue and social impact projects.

Funding for nanotechnology has been dramatically increased under FP7 (which runs from 2007 to 2013) to €3.5 billion, representing 6.5% of the total budget of €53.2 billion. The EU is also encouraging member states, and particularly industry, to increase investment in nanotechnology in R&D.

The other key policy concern expressed in the Communications is related to health and environment. The EC is of the view that existing legislative frameworks are sufficient to cover the potential hazards of nanotechnologies, but that member states and agencies will need to be proactive in updating terminology, definitions, minimum requirements and labelling codes to ensure that nano-materials are properly classified and subject to the appropriate scrutiny.

It should be noted that some groups, such as the European Trade Union Confederation, believe that the EC should be doing more in addressing safety concerns.

Other issue identified by the EC as important but which have not yet seen significant action include:

- ▲ *Greater coordination of national research programmes and investment to ensure that Europe has teams and infrastructures that can compete at international-level.*
- ▲ *Other competitiveness factors should not be overlooked, such as adequate metrology, regulations and intellectual property rights so as to pave the way for industrial innovation to be carried out and lead to competitive advantages, both for large and small- and medium-sized companies.*
- ▲ *Activities related to education and training are of great importance; in particular, there is scope in Europe to improve the entrepreneurial character of researchers as well as the production engineers positive attitude to change.*
- ▲ *Social aspects (such as public information and communication, health and environmental issues, and risk assessment) are further key factors to ensure the responsible development of nanotechnology and that it meets people's expectations. Public and investors' confidence in nanotechnology will be crucial for its long-term development and fruitful application.*

Regional level

The European Commission has proposed a number of actions by which regional institutions can help support the development of nanotechnology in line with EU:^{2,24}

1. increase investment and coordination of R&D to reinforce the industrial exploitation of nanotechnologies whilst maintaining scientific excellence and competition;
2. develop world-class competitive R&D infrastructure ("poles of excellence") that take into account the needs of both industry and research organisations;
3. promote the interdisciplinary education and training of research personnel together with a stronger entrepreneurial mindset;
4. ensure favourable conditions for technology transfer and innovation to ensure that European R&D excellence is translated into wealth-generating products and processes;
5. integrate societal considerations into the R&D process at an early stage;
6. address any potential public health, safety, environmental and consumer risks upfront by generating the data needed for risk assessment, integrating risk assessment into every step of the life cycle of nanotechnology-based products, and adapting existing methodologies and, as necessary, developing novel ones; and
7. complement the above actions with appropriate cooperation and initiatives at international level.

In addition to the suggested actions of the EC, it is useful to refer to reviews of regional policy by other countries, such as the report produced in March 2007 by the UK's Council for Science & Technology, **Nanotechnologies: A Review of Government's Progress on its Policy Commitments**. The review identified a number of roles for government:

Co-ordination and Review: *strategic cross-government co-ordination of different departments and agencies, particularly in the area of research, with one government department, body or agency given the responsibility to champion the policy.*

Research Funding: *rather than relying on the EC and the local research community to direct research activities, the government should develop a program of strategic research spending in order to achieve its specific local objectives.*

International Engagement: with other countries and international organisations in standards and regulation development and in collaborative research.

Interface with Industry: streamline the interface between government, industry, non-governmental organisations (NGOs) and the media to aid communication.

Regulation: to allow existing health, safety and environmental regulation to be implemented effectively for nanotechnologies.

Voluntary Reporting Scheme: to encourage industry to act responsibly in regards to new nanotechnology applications in the interim period while regulations are being updated.

Public Engagement: maintain an ongoing programme of public engagement and conduct deeper and more in depth deliberative dialogue processes to deliver results of greater value to policy makers.

Stimulating technology transfer from nanoscience to business

The recommendations below are derived from a two day workshop “Nano2Business” held at Warsaw University of Technology on 7th and 8th February 2007.⁴² The main focus of the discussions was on the best organisation for technology transfer incubators, technology transfer networks, and on identifying the main barriers to technology transfer, with particular focus on nanotechnologies.

The major barriers to the transfer of nanotechnology to industry were identified as being related to the specific character of nanotechnology as a research area:

- ▲ The difficulties of building an ideal nanotechnology transfer team with a combination of skills in physics, chemistry, biology, materials science, modelling, business and management
- ▲ The communication barriers resulting from the broad range of fields covered by nanotechnology. This leads to a poor understanding of what nanotechnology is. The production of nanostructured metals, 40 nm electronic chips, or nanoparticles for drug delivery involve completely different technologies, but they are all labelled “nanotechnology”. A negative assessment of one area of nanotechnology may lead to negative assessments of the other fields.
- ▲ Over-use of the term “nano” may become a future barrier for nanotechnology transfer, since various institutions and incubators of an average level may have a similar “nano” label which in recent times has applied only to elite organisations.
- ▲ The systems of funding of research and assessment of researchers, or research institutes are not always conducive to the efforts of researchers to develop practical applications.

- ▲ Technology transfer is the commercialising of intangible assets. That means, the inventor has frequently to propose a project whose value is not easily measurable and there are no tangible assets to guarantee the investment will be profitable.
- ▲ A long term strategy based on excellence is needed to develop efficient technology transfer incubators or networks. To achieve success may need over 10 years work. At intermediate stages evaluation of the incubators or the network may be difficult.
- ▲ The advanced knowledge needed to establish a successful network or incubator. The best incubators and networks presented in the report are the result of over 10 years work by a community of scientists, administrators, local authorities and business, with strong leadership. Much of the ‘know-how’ which enables the successful operation of such technology transfer centres is in the detail and cannot be easily transferred without the transfer of people.

Therefore the main recommendations for efficient technology transfer are:

- ▲ Learning from the best is a tremendous opportunity for Europe. This can be done by establishing collaboration with the leading technology transfer incubators or networks. The New Member States especially can obtain the benefit of learning from the best examples and so avoid many of the errors made previously.
- ▲ Education: business skills taught at universities, educating technology translators, network managers and incubator managers. This knowledge would strongly help to further nanotechnology in the difficult field of transfer to business.
- ▲ Improving the organisation of science.
- ▲ Improving the assessment of researchers and institutes or faculties to achieve strong motivation for researchers and to support new spin-offs or other forms of technology transfer.
- ▲ Improving the way research projects are generated and evaluated, so that there is sufficient, in-depth, research by large research groups.

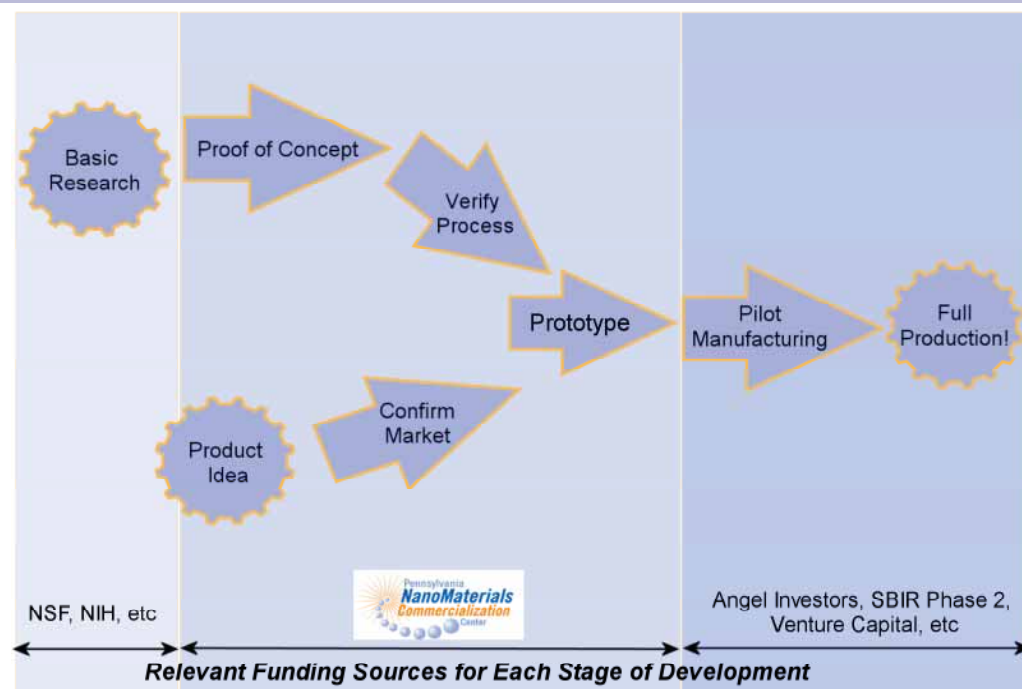
A nanotechnology incubator

The Pennsylvania NanoMaterials Commercialization Center (www.pananocenter.org) facilitates the commercialization of nanomaterials technologies, and builds upon Pennsylvanias excellence in advanced materials research, development and manufacturing. The center uses a unique model to proactively create partnerships between government organizations, universities, entrepreneurs, small and large companies to match nanotechnology research with innovative new ideas, and then accelerates the development of those ideas into new products, new companies and growth for the region and the country.

The Center was founded in 2006 under the auspices of the Pittsburgh Technology Council by a consortium of four western Pennsylvania companies; Alcoa Technology, Bayer MaterialScience, PPG Industries and US Steel. Today, the Center enjoys partnerships with Carnegie Mellon University, University of Pittsburgh, Penn State University, the Department of Community and Economic Development for the Commonwealth of Pennsylvania, Air Force Research Labs and approximately 300 companies, organizations and individuals involved in nanotechnology.

The Center plays a critical role in accelerating the commercialization of nanomaterials research for new and enhanced products critical for U.S. commercial and defense needs.

Funding available from the Pennsylvania NanoMaterials Commercialization Center is typically used to bridge the “Valley of Death” phase of development, between the technology proof-of-concept stage and the production of a customer-relevant prototype product.



[Graphic reprinted by permission of the Pennsylvania Nanomaterials Commercialisation Center, Pittsburgh, PA, USA, all rights reserved.]

NANOTECHNOLOGY IN SPAIN & CATALONIA

Nanotechnology R&D has experienced explosive growth in Spain over the last few years, much as it has in most other advanced countries. The Nanospain Network (www.nanospain.org) is a voluntary grouping of government, research and commercial representatives that currently (September 2008) has a membership of 248 research groups of over 1200 researchers. This compares to a membership of only 110 researchers in 2003.

This rapid growth is also reflected in the increased focus on nanotechnology by the Spanish government in its national research plans.⁴³ Plan Nacional de I+D+I (2001-2003) hardly mentioned nanotechnology, however Plan Nacional de I+D+I (2004-2007) included Nanoscience & Nanotechnology as a Strategic Action⁴⁴ and during the 4 years of the plan 250 actions with total funding of over €17,5 million were approved. Plan Nacional de I+D+I (2008-2011) continues and expands this strategic action, defining seven broad scientific lines of research.

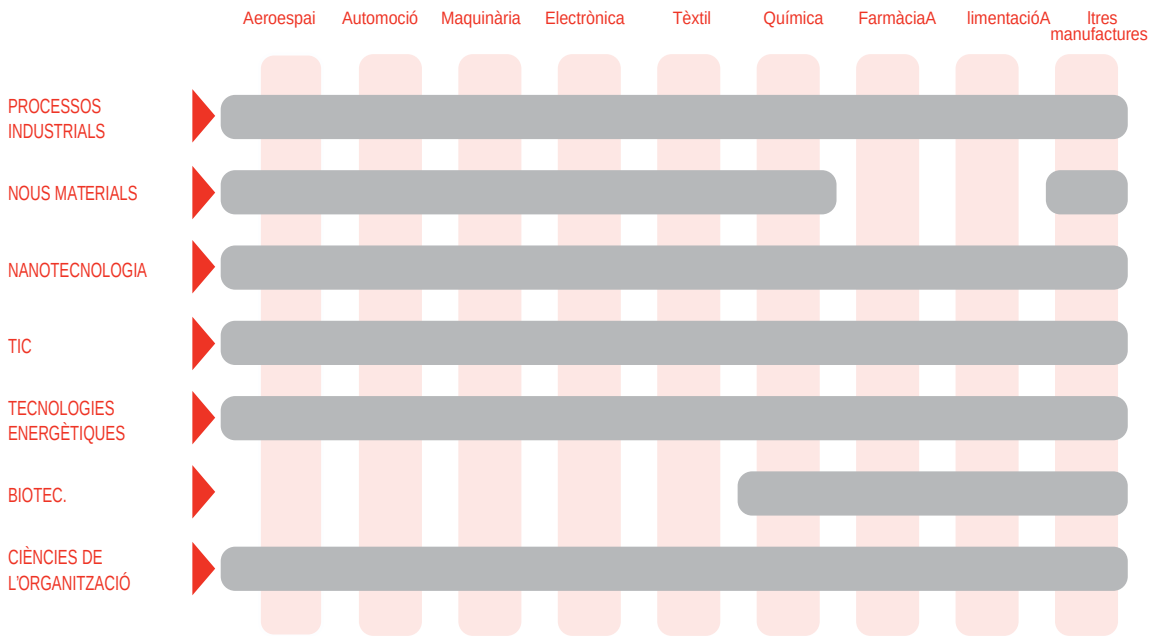
In addition to the national plans, Plan Ingenio 2010 is supporting a number of large nanotechnology initiatives, as are the various autonomous communities, foremost amongst them Catalonia and Pais Vasco, with some significant investments also by Valencia and Andalucia.

While this is a substantial increase in the investment in nanotechnology R&D, it must be put in perspective against other regions.⁴⁵ EOn a per capita basis Spain invests very little in nanotechnology, not only in comparison to traditional heavyweights such as the US, Japan and Germany, but also in comparison to many countries smaller in population, such as Ireland, Israel and Australia. Spain even lags behind several eastern European countries.

Furthermore, the Spanish investment is fragmented, with many small, uncoordinated initiatives at both national and regional levels. To date, there has also been relatively little participation by industry,⁴⁶ either via indirect involvement through funding science parks and technology incubators or by participating directly in specific research projects. The result is that the Spanish effort does not optimise its potential impact.

France, for instance, besides from a national program of nanotechnology in its universities and research centres, has also established five major nanotechnology clusters⁴⁶ (associations, within a given geographic area, of companies, research centres and academia working together around innovative projects) to focus on particular aspects of nanotechnology. One of the largest clusters, Minatec (www.minatec.com) which focuses on combining micro-and nanotechnologies with embedded software, on its own employs 4000 people – this single site is larger than the entire Spanish nanotechnology network.

Catalonia was one of the early leaders investing in nanotechnology within Spain, establishing a dedicated research institute,⁴⁸ the Institut Català de Nanotecnologia (ICN) and several nanotechnology laboratories within other Catalan institutes such as Institut de bioenginyeria de Catalunya (IBEC - www.ibecbarcelona.eu) and Institut de Ciències Fotoniques (ICFO - www.icfo.es). The ICN has recently collaborated with CSIC to establish a national institute, Centro de Investigación de Nanociencia y Nanotecnología (CIN2). Altogether there are over 37 groups⁴³ in various institutes, technology centres and universities within Catalonia registered as being involved with nanotechnology. Catalan funding for research and technology transfer is governed by the Pla de Recerca i Innovació de Catalunya 2005-08,⁴⁹ which identifies nanotechnology as one of its seven strategic sectors.



[Source: <http://www10.gencat/pricatalunya/recursos/PRI-llarg-CAT-2005-06-06.pdf>. © Generalitat de Catalunya.]

Recent figures⁴³ show that, although there are variations between the various regions in Spain, in general funding for nanotechnology R&D comes from:

Source	% funds
National	53%
Autonomous communities	22%
EU	13%
Industry	12%

A number of Catalan companies in a number of important sectors are already utilising nanotechnologies in both production processes and end products. A recent report⁵⁰ by CIDEM (Centre d'Innovació i Desenvolupament Empresarial) highlights a number of these, including:

Activery Biotech SL (medicine/biology), a company formed in 2003 which uses a proprietary method to produce nanoparticles for applications in pharmaceuticals, pigments and cosmetics.

Rovalma SA (automotive), a company formed in 1977, has invested heavily in nanotechnology based R&D to develop improved steels and special alloys for tools and other industrial applications, which it now exports to the EU, USA and Asia.

Matgas 2000 AIE (energy), is a non-profit group dedicated to meet the demand for applied R&D in materials, gases and energy. Among several lines of nanotechnology based research, one of the most successful is that relating to photovoltaics for production of solar energy.

Aromics SL (food), founded in 2005, is utilising magnetic functionalised nanoparticles to develop sensing platforms for pathogens, in food, environmental and clinical samples.

Color Center (textiles), founded in 1978, is developing nano-encapsulation techniques to allow beneficial substances to be incorporated into textiles and slow-released, provide benefits over longer time periods.

However besides from these few early success stories, the general barriers to establishing successful high-tech start-ups would seem to also be impacting the development of local nanotechnology based businesses:

- ▲ High costs of starting up a company,
- ▲ Long waiting times for official approvals and licenses,
- ▲ Difficulties in securing funding for prototype and proof of concept developments,
- ▲ Cultural impediments such as the negative view of business failure, and
- ▲ Lack of strong technical and R&D capability within local companies (especially SMEs) to facilitate technology transfer.

CONCLUSIONS

Nanotechnology is not simply an isolated scientific breakthrough that might have a few important applications —nanotechnology is a major theoretical and technical advance that will affect all branches of science and all sectors of industry.

The origins of this revolution have been long in the making, with many different fields of science steadily progressing until a critical convergence was reached in the late 1990s. At this point, newly available tools and new scientific understandings enabled new discoveries and new practical applications to develop at a rapid rate. The potential economic and social impact was quickly realised and governments all over the world began to invest – world public spending grew from just over US\$400 million in 1997 to well over US\$4000 today.¹⁶

This level of investment sends a very strong signal to both private industry and society in general, as to the strength of belief in the potential of nanotechnology by scientists and public officials.

Importantly, there are significant differences between the current nanotechnology revolution and the genetics revolution of the 1990's, which also represented a major scientific and technical breakthrough and attracted similar amounts of public and private investment — and media attention.

The vast majority of near-term genetics applications are primarily in two important sectors: medicine and agriculture. Medicine is a field which develops new applications slowly, because of the rigorous and lengthy clinical trial requirements. Agriculture, with its environmental aspects and food safety issues gave rise to the GM debate and the subsequent restriction of commercial application of genetic technologies. Thus, although the genetics revolution appeared to promise much, the general public has to date seen relatively little immediate impact on daily life.

In contrast, nanotechnology is not limited to just a few sectors; it will have a significant impact on all sectors of industry and human endeavour, and is already in everyday consumer products such as clothing, cosmetics and sporting goods.

Perhaps the best analogy would be to compare the onset of nanotechnology with the introduction of electricity. Much as it is impossible to imagine living today without electricity, future generations are likely to be completely dependent on nanotechnologies. Even if, as occurred with GM, the development of some aspects of nanotechnology are slowed due to social concerns (for example nano-particles), this will not impede the continued rapid development of other nanotechnologies.

The challenge for regional governments, in the face of this worldwide technological phenomenon, is to ensure that local industry is empowered to assimilate these new

technologies and remain internationally competitive.

Additional challenges include the need to build up a large, multi-disciplinary educated workforce, address public concern over health and environmental issues and harness the limited local resources available to try and secure a niche that can provide a new source of economic growth for the region.

It is hoped, within the scope of this brief document, that the reader has achieved a general understanding of nanotechnology, its economic, industrial and social implications and its potential to improve quality of life on a global scale. For more in-depth information the reader is recommended to access the many excellent, detailed reports that have been produced on specific topics, a selection of which are listed in the Appendix "Recommended Reading".

RECOMMENDATIONS

RECOMMENDATION 1: DEVELOPMENT OF KEY NANOTECHNOLOGIES TO SUPPORT CATALAN INDUSTRY

There is already a strong Catalan nano-technology research community, with the Institut Català de Nanotecnologia (ICN), Centro de Investigaciones en Nanociencia y Nanotecnología (CIN2), the Institut de Ciències Fotòniques (ICFO), Institut de Bioenginyeria de Catalunya (IBEC), Centre for Research in NanoEngineering (CRNE), Centre de Recerca en Bioelectrònica i Nanobiociència (CBEN), Centro Nacional de Microelectronica (CNM), Institut Català d'Investigació Química (ICIQ), Institut d'Investigacions Químiques i Ambientals de Barcelona (IIQAB), MATGAS 2000 AIE, Parc Científic de Barcelona (PCB) and Instituto de Ciencia de Materiales de Barcelona (ICMAB) amongst others, forming a solid base of several hundred researchers working at the forefront of their fields.

However, although each of these centres makes some effort in technology transfer and there exist dedicated technology transfer agencies established at a national and Catalan level, the rate and success of technology transfer appears to be very slow¹⁴. As noted earlier, this is a problem in general across Europe as compared to the US and Asia, but even within Europe, Spain is a poor performer.

One reason for this may be that the rate of private investment in R&D&i by Spanish companies is very low, thereby affecting their ability to assimilate new technologies — for technology transfer from research to business to take place, there must exist local companies with the technical and manufacturing capabilities to receive the technology.

In order for Catalan industry to remain competitive in the nanotechnology equipped future, it is vital that well-performing technology transfer mechanisms be established to ensure that local industries can rapidly assimilate and adopt the technologies being developed both locally as well as internationally. Local industries must also be encouraged to develop high-tech capabilities, such as trained technicians and innovative manufacturing practices, to ensure they are able to assimilate the new technologies.

Key industries which are likely to require nano-technologies to remain competitive are micro-electronics, car manufacturing, medical devices and drugs, textiles, construction materials and consumer products utilising fine chemistry such as cosmetics and detergents. Several of these are quite important to the Catalan economy.

Actions that might be considered by the Catalan parliament include:

- ▲ *Establishing information resources to enable local companies, especially PYMES who often lack good access to international information, to be kept updated with the latest advances in technologies relevant to their industry;*
- ▲ *Ideally, some of these information resources could be pro-active, such as extension officers who travel from company to company presenting information and opportunities;*
- ▲ *Promoting technology transfer in the form of industry (technological centre)-academia matchmaking, grants or tax-breaks to support R&D&i, pilot projects, proof of concept and scalability of processes;*
- ▲ *Streamlining the bureaucratic processes involved in establishing a new business, to reduce the time and costs needed to launch a start-up high-tech business, and*
- ▲ *Promoting the development of an educated, multidisciplinary workforce. This would include not only reviewing the courses offered by universities and technical colleges for youth, but also stimulating the retraining or supplementary training of older workers.*

RECOMMENDATION 2: SELECT AND FOCUS EFFORTS ON ONLY A FEW KEY AREAS TO BECOME NICHE LEADER

Although it is important for Catalan science and industry to maintain a minimum level of investment in most key fields of nanotechnology, it is unrealistic to expect that excellence, let alone leadership, will be achieved in all. The resources available locally for such R&D activities pale in comparison to those being deployed by some regions of the US, Japan and even EU countries such as Germany, France and the UK.

However it does not necessarily follow that Catalan science and industry cannot attain world leadership within some niche areas, perhaps by adopting a “cluster” model to bring together companies and research groups. The process of choosing the appropriate areas of focus would need to involve careful evaluation of the different options, but a number of scenarios suggest themselves.

Catalonia has significant strengths in biomedicine, animal health, food, renewable energies and construction, amongst others. Overlaps between these capabilities and burgeoning nanotechnologies would be most likely to provide a strong base upon which to build niche expertise.

For example, a number of recent reports have highlighted that despite the massive R&D programs of the US, Japan and the EU, investment into research and development of nano-metrology — measurement of the physical, chemical, toxic and environmental safety of nano-materials — has been badly neglected.

Given Catalonia's strengths in biological fields such as biomedicine, animal health and food processing, this might present an opportunity for the development of Catalan centres of expertise and commercial services in nanotechnology measurement and testing, in particular as regards to the human health and general environmental toxicity of nano-particles.

There is little doubt that testing of nano-particles and other potentially harmful nano-materials will become mandatory in the future. Given the large number of products expected to incorporate nano-particles, the market for standardised testing and toxicity evaluation will be very large.

If Catalonia elected this as a niche to be developed, potential actions would include:

- ▲ *Focusing local research efforts into associated projects;*
- ▲ *Promoting the plan to local and new industry and offering incentives to become active in commercialising the technologies;*

- ▲ *Identifying relevant R&D centres and/or companies elsewhere and incentivising them to joint venture or co-operate in other manners with the activities in Catalonia;*
- ▲ *Establishing and equipping a dedicated mixed commercial / research laboratory to develop standard tests and to offer these on a commercial basis to companies with nano-technology products, and*
- ▲ *Promoting initiatives for local industries to implement nanotechnologies that add value to existing operations, improving their international competitiveness.*

Similar plans could be developed for other identified focus niche areas that build on existing Catalan strengths, such as nano-materials and nanotechnologies for use in residential housing construction, nanotechnology in food processing, etc.

Metrology

Metrology, from Ancient Greek 'metron' (measure), and 'logos' (study of) is the science of measurement.

Metrology is so important in nanotechnology that it forms a sub-field of its own. Nano-structures and nano-particles pose particular challenges in measurement because there are so many aspects that need to be measured — size, shape, length, strength, brittleness, elasticity, conductivity, colour, solubility, density — as well as characteristics individual to different types of structures, such as the arrangements of different parts relative to each other or the way in which structures join or are folded.

Both science and industry require good metrology, standards and calibrations to be able to compare results, ensure quality control, and measure production. Metrology is also vital to enable monitoring of health and environmental effects.

Currently, there are some tools available (such as electron microscopes) to measure some features of nano-structures, but usually these are very expensive and require very strict laboratory environments. Scientists and industry urgently need reliable metrology services and equipment in order to progress with their endeavours.

[Image: FEI® Magellan™ 400L FEI electron Microscope.]



RECOMMENDATION 3: PRO-ACTIVE POLICIES ON HEALTH & SAFETY

The public's main concern is safety, both in terms of human health and the environment. The public has little trust in private industry to self-regulate and only slightly more trust in public agencies to use existing laws to regulate new technology.

Although such regulation will ultimately be enacted and harmonised at the national and EU level, policies at this level are slow to evolve and the Catalan parliament may wish to consider interim measures such as updating Catalan health and safety regulations, introducing compulsory or voluntary schemes for product labelling, etc.

Key issues that need to be addressed include:

Regulation

- ▲ *Labelling laws covering all products that utilise nanotechnologies to declare the type of technology and its safety profile.*
- ▲ *Laws governing the use of the word 'nano' to prevent spurious and misleading marketing.*
- ▲ *Environmental safety regulations regarding disposal or other release into water and the environment of those nanotechnologies deemed to pose the greatest risk, such as nano-particles and nano-tubes.*

Safety testing

- ▲ *Mandatory safety testing of those technologies deemed to pose the greatest health and environmental risk, such as nano-particles or nano-tubes in applications of potential risk.*
- ▲ *Mandatory health and safety warnings for products with potential risks.*

The positive potential of nanotechnology for the environment should also be promoted, with support for the development and adoption of new methods to monitor, control and remediate pollution.

APPENDIX 1: Recommended reading

The following is a selection of publicly available reports and website links which the author recommends for more detailed information on specific topics.

General information on nanotechnology

European Commission (2004): «Nanotechnology - innovation for tomorrow's world», a clear, non-scientific explanation of nanotechnology, its major applications, risks and benefits.

CIDEM (April 2008): «Introducció a les nanotecnologies i les nanociències», a recent, well written introduction to nanotechnology with reference to commercial nanotechnology activities in Catalonia.

Fundación de la Innovación Bankinter (2006): «Nanotechnology: the industrial revolution of the 21st century, a very well written and informative non-scientific discussion of nanotechnology and its implications, with a Spanish focus.

Wikipedia (www.wikipedia.org) has a many detailed sections on different aspects of nanotechnology, including nanorobotics, nanoelectronics, nanomaterials and nanoparticles.

Applications & markets for nanotechnology

Lux Research (2008): «The Nanotech Report 5th Edition», in-depth and well-regarded privately produced report on nanotechnology industry and market trends.

Hessen Ministry of Economy, Transport, Urban and Regional Development (August 2008): «Application of Nanotechnologies in the Energy Sector», in-depth and well illustrated review of how different nanotechnologies may affect the production and supply of energy.

National Cancer Institute (January 2004): «Cancer Nanotechnology - Going Small for Big Advances; Using Nanotechnology to Advance Cancer Diagnosis, Prevention and Treatment», informative and well illustrated brochure on the many ways in which nanotechnology is expected to improve medical treatments, in particular cancer.

NANOCAP Project (November 2007): «Applications of Nanotechnology: Environment», clear and well illustrated document describing nanotechnologies under development for solving important environmental issues.

Health & safety

Website of the University of Wisconsin-Madison, Nanoscale Science & Engineering Center (www.nsec.wisc.edu/NanoRisks/NS--NanoRisks.php), excellent resource listing of public & private industry documents relating to all aspects of nanotechnology health & safety issues.

SwissRe (2004): «Nanotechnology, Small Matter, Many Unknowns», well written non-technical review of the unknowns and risks of nanotechnology, from the perspective of an insurance company.

Consumer products that use nanotechnology

Nanotech Project website (www.nanotechproject.org) in particular the Nanotechnology Consumer Products Inventory (www.nanotechproject.org/inventories/consumer/); a concise and regularly updated listing of nanotechnology consumer products worldwide.

Research activities in nanotechnology

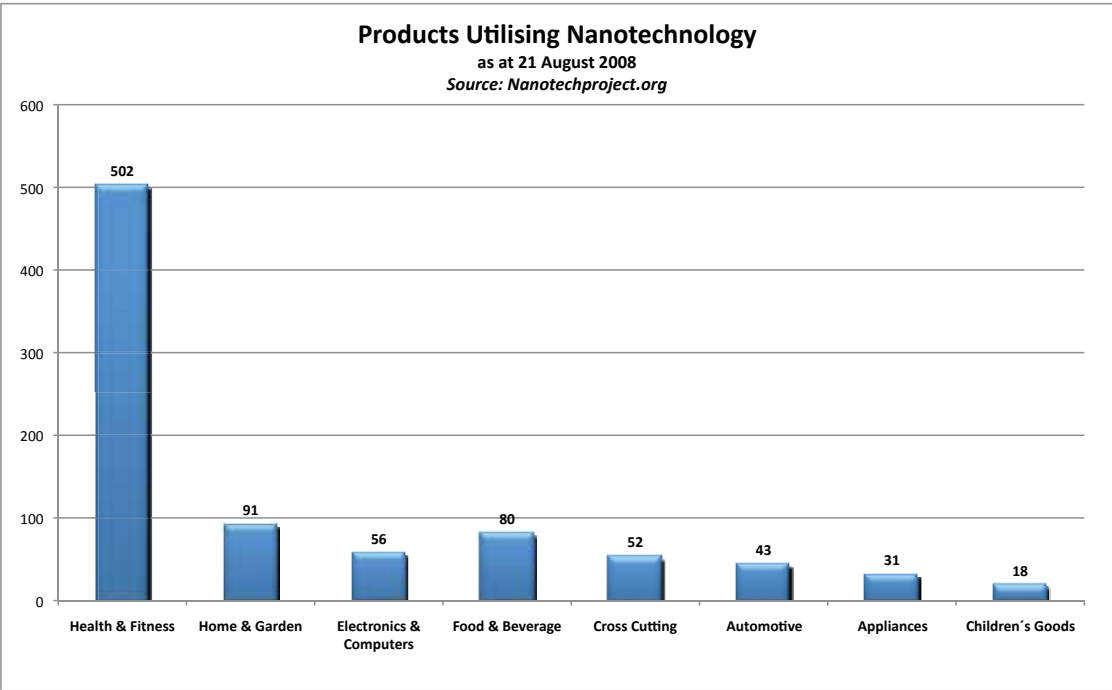
European Commission CORDIS Nanotechnology homepage (cordis.europa.eu/nanotechnology/); central point for all EC sponsored research in nanotechnology.

Nanotechnology in Spain

Phantoms Foundation: «Nanociencia y Nanotecnología en España, 2008», a comprehensive review of the current state of nanotechnology research activity and funding in Spain.

APPENDIX 2: Applications of nanotechnology

Everyday applications of nanotechnologies are not just a future prediction, they are already available worldwide in a range of consumer products.^{4,6} Some of the applications already to be found on the market include cosmetics and sunscreen lotions, more flexible and resistant tennis rackets and non-scratch glasses.^{52,53}



Breakdown by consumer category of the inventory of nanotechnology-based consumer products⁵⁴

Most reports on nanotechnology predict that nanotechnology will gradually emerge in the medium term,¹ with some of the most revolutionary changes in everyday life expected to be in hygiene and communications, with large changes also in food and transport.

The sections below provide a brief overview of some of the key applications that are expected to emerge in various sectors.

Medical applications

EThe potential of significant breakthroughs in medical technologies is one of the great promises of nanotechnology.⁷ Improved diagnostics to detect diseases earlier, treating cancer,⁵⁵ improved implants to repair damaged bones, joints and tissues, improved drug delivery mechanisms to provide better treatments with reduced side effects and even a future with implanted nano-robots that could clear clogged arteries and fight off diseases, are all visions that now seem to be in reach.

However it must be understood that any treatments that involve nano-materials entering or contacting the body must pass strict clinical trials and demonstrate safety and efficacy. The typical timescale for a new drug, from identification of the candidate molecule to approval for widespread marketing is typically 12 years or more.⁵⁶ Since most nanotechnologies involve entirely new processes and/or materials, the time taken to prove non-toxicity and safety may be even longer.

Thus although the eventual impact of nanotechnology on medicine is high and a significant amount of current R&D investment is focussed in this area, significant applications such as those described below are not expected to be widely available within the next decade.

Some of the most exciting potential applications include:

Nanotechnology-based coatings or structured surfaces that can improve surgical equipment such as blades and needles, and the bioactivity and biocompatibility of implants.

It is already possible to manufacture surgical blades of extreme sharpness and low friction that are highly suited to optical- and neurosurgery, using plasma polished diamond nano-layers placed on the cutting edges of metal blades.⁵⁷

Currently many implants are made of steel and plastic components, such as titanium, that have smooth surfaces. Although these materials are non-toxic, in that they do not degrade and release poisons into the body, they are not always highly bio-compatible. This means that the body's tissues often do not integrate very well with the smooth surface, forming scar-like tissues around the implant, which can have negative effects on bloodflow and other bodily processes around the site of the implant.

By directly modifying the surface or applying thin layers of other nano-structured materials, to create surfaces that have pores and other surface features similar to natural tissues, it has been shown that the body's tissues actually attach and grow into the surfaces, thereby holding the implant in place and avoiding the formation of scar tissue.

Scaffolding for regrowth of bone and other damaged tissues. A more advanced application of the phenomenon described above, instead of just nano-structuring a surface, an entire implant is nano-structured in such a way as to encourage tissue to grow inside it, thereby providing a 3-D scaffold for tissue regeneration. This process has already been demonstrated for stimulating bone regrowth and could in future be used to provide scaffolds for repair of organs, damaged muscle and other tissues.

Drug delivery. Drugs are an extremely potent method of treating disease, however they often have severe and unwanted side effects when they spread throughout the body. Medical practitioners are therefore seeking ways to target the delivery of drugs only to the specific organs or physical locations where treatment is needed. In this way they could significantly reduce the dosage thus saving money and avoiding or reducing many of the unwanted side

effects.

Because nano-particles are of a similar scale of size to drug molecules and can easily travel through the body's arteries in the bloodstream, scientists are exploring many novel ways of combining nano-particles and drugs to achieve **targeted delivery** to the desired area of treatment.

These include; attaching drug molecules to the surface of nanoparticles, which are guided to the target location by external forces such as magnets; enclosing drug molecules in nano-cages that open only when they reach the target site; enclosing drug molecules in a nano-particle that slowly decays, thereby giving a sustained release of the drug over time; attaching the drug molecules to nano-particles that don't move, so they can be injected into a specific site (such as a tumour) and stay there; and many other techniques.

Miniaturised devices. Nanotechnology will also potentially enable devices to be shrunk sufficiently so they can be implanted in the body. These could be diagnostic devices, to measure key indicators of a person's condition (eg insulin levels for diabetics), drug delivery devices that could release small amounts of a drug directly into the bloodstream or a specific tissue when required, bionic devices to replace non-functioning tissues, (eg artificial retinas for some types of blindness), and even artificial organs such as hearts, kidneys, etc.

Information & Communication Technology (ICT) Applications

The advantage of smaller, more powerful computing and communication devices is self-evident. Modern society has become accustomed to a steady rate of improvement in such devices, however a theoretical limit is being reached - when the size of features on chips approaches 4nm, at which point nano-effects appear and the materials change behaviour.

This means that the limit of current technologies will be reached within the next 1-2 decades, and further improvements will only be achieved if scientists can master the peculiar properties at the nano-scale and develop new, commercially viable technologies to replace the micro-electronics currently being used.

Asides from providing a mechanism for continued improvement of existing applications in computing, data storage and communications, nanotechnology also offers the potential of several completely new types of products becoming available.

Flexible or paint-on visual displays. One of the properties that often changes dramatically at the nano-scale is conductivity. In particular, several different types of polymers (plastics) have been shown to become conductive at the nano-scale. This opens up the opportunity to produce visual devices (such as TV screens) made of flexible materials, potentially even of materials that can be painted on to a surface.

Textiles with embedded electronics. Similarly, flexible wires could be woven into textiles, enabling clothes, bandages, bedsheets and furniture coverings to be connected to sensors, power sources, communications equipment and computers. This creates a vast potential for new applications, from bandages that can detect the type of infection in a wound and release the appropriate drug, to clothes that can automatically adjust to be warmer or cooler depending on the ambient temperature and the person's level of activity, to accessories that can change colour depending what other clothes are being worn or even clothes with built-in mobile phones and computing devices.

Bio-electronics. The shrinking of electronics down to the molecular scale also creates possibilities to directly interface electronics with biological processes. Examples include using the processes of photosynthesis to power miniature circuits, integrating sensors directly into plants (such as fruit trees or grape vines) to enable water and nutrients to be optimised and ultimately directly interfacing electronics to neurons in the body to enable artificial limbs, retinas and other organ replacements to be controlled directly by the brain.

NANOTECHNOLOGY IN NATURE - Crystal eyes

Scientists have discovered a species of brittle star (*Ophiocoma wendtii*) whose outer skeleton is covered with nano-structured crystalline micro-lenses, turning the whole body of the hairy star into one complex eye.

The visual system of lenses in the species is the first of its kind observed in nature and is superior to any manufactured lenses. The compound eye allows the organism to detect predators and seek out hiding places.

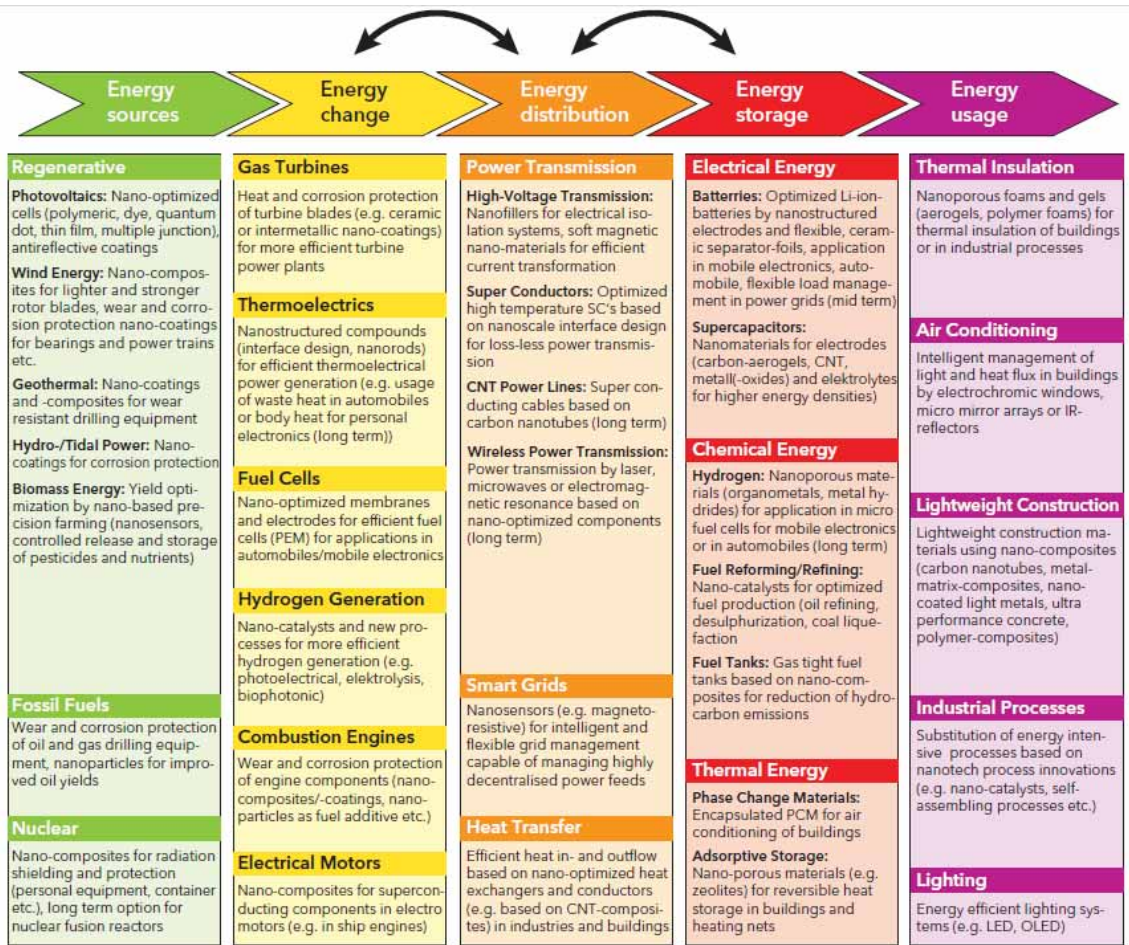
[Source: brittle star found covered with optically advanced "eyes", National Geographic, August 22 2001; Nanotechnology Innovation for tomorrow's world, European Commission, EUR 21151EN, 2004]

Asteropora annulata. [Image reprinted by permission from the NOAA]



Energy applications

UA key area expected to benefit greatly from nanotechnology is that of energy production, storage and usage.⁵⁸ The effect of nanotechnology can be two-fold; as devices are made smaller and more energy efficient, they require less energy; and the energy itself is produced, stored and transmitted more efficiently, thus resulting in significant savings in both financial and environmental terms.



Examples for potential applications of nanotechnology along the value-added chain in the energy sector (source: VDI TZ GmbH)

[Application of nanotechnologies in the energy sector, available at http://www.hessen-nanotech.de/mm/NanoEnergy_web.pdf, and reprinted by permission from the VDI Technologiezentrum GmbH Düsseldorf.]

Energy production improvements are anticipated in a number of areas:

Fuel cells can be thought of as batteries where the chemicals are allowed to react and the resulting exchange of electrons is diverted to provide an electric current. The efficiency of fuel cells is highly dependent on the catalytic surface on which the reaction takes place and which must harvest the electrons. Nano-structuring these surfaces to better control the rate of reaction and capture more of the electrical energy has the potential to dramatically increase the efficiency of such fuel cells. Of particular

interest are hydrogen fuel cells that run on hydrogen and oxygen to produce water and electricity. If these non-polluting fuel cells can be made efficient they could play a big role in reducing dependence on fossil fuels.

Photovoltaics or “solar cells” are films of semiconductors that convert sunlight to electricity. The problem with current photovoltaic materials is that they convert only certain wavelengths of light to electricity and the rest of the light is wasted as heat or reflected back into the air. By nano-structuring composites of ultra-thin semi-transparent layers of different materials, scientists hope to be able to construct lightweight materials that are much more efficient at converting light to electricity, and thereby make solar energy a cost effective substitute for fossil fuels.

Energy storage, particularly of gaseous fuels such as hydrogen is also a focus for nanotechnology research. Hydrogen gas is highly explosive, so storing it in traditional high pressure cylinders is dangerous if it is to be used more widely as a fuel. Techniques are being developed to create nano-porous solids that can absorb large amounts of hydrogen (much as a sponge soaks up water) which could then be used to store and transport the hydrogen safely, with minimal risk of explosion.

Energy efficiency improvements are being researched in a number of areas, including better insulation materials for buildings and refrigeration equipment, more efficient lights and video displays, and improved sensors to control heating and cooling systems.

Material applications

Materials science developments using nanotechnology are far-reaching and are expected to impact upon virtually all sectors. Furthermore they represent the first wave of commercially available applications, with many already on the market.

Nano-particles, as described earlier, are already used in substances as varied as car tyres and cosmetics. Their inclusion in materials can significantly modify the functionality of the material, such as making the material stronger, more resistant to wear, conducting of electricity, absorbing of UV, resistant to corrosion, even anti-microbial (as in the case of silver particles embedded into material for socks and underwear).

Surfaces can be nano-structured to modify their properties in different ways, for example, making the surface scratch-proof, more or less wettable, self-cleaning, photovoltaic (converting light into electricity), insulating, abrasive, smooth, durable or soft.

Composites, which are mixtures of materials or different layers bonded together, are also expected to see significant improvements, in particular those designed for extreme conditions such as aeronautics, marine and space environments.

New classes of materials are also anticipated. Of special interest are those where an organic layer of biologically active molecules are bonded to the surface of inorganic materials such as glass, plastic or metal. These could be used as sensors, catalysts or even for everyday applications such as bathroom surfaces that resist mould.

NANOTECHNOLOGY IN NATURE - Strong and beautiful

Nacre, or mother of pearl, is the iridescent layer that composes the inner surface of the shell molluscs. Besides from being beautiful, this material is extremely strong and light, providing protection for the mollusc from predators.

The main component of nacre is the mineral aragonite, which on its own would be very brittle. In nacre however, millions of tiny crystals are held together in nano-structures by highly elastic proteins, making the nacre thousand of times stronger than regular aragonite crystals.

[Sources: Julian H. E. Cartwright and Antonio G. Checa, «The dynamics of nacre self-assembly», J R Soc Interface, June 22 2007; 4(14):491–504; Nanotechnology Innovation for tomorrow's world, European Commission, EUR 21151EN, 2004]

This image from Wikimedia Commons was created by Chris 73 and it is free available at <http://commons.wikimedia.org/wiki/Image:NautilusCutawayLogarithmicSpiral.jpg>, under Creative Commons cc-by-sa 2.5 license.



Manufacturing & industrial applications

The first impact of nanotechnology in manufacturing and industrial applications is expected to be in enabling improvements to existing equipment and processes:⁵⁹

- **Miniaturisation of sensors** will enable better monitoring and control of production processes as well as enabling continuous monitoring of stress and corrosion in large structures such as bridges, buildings and tunnels;
- **Improved filters, membranes and catalysts** will improve efficiencies of chemical reactions and separations;
- **Nano-structured surfaces** will be more durable and result in better flowing pipes with less build-up of unwanted deposits;
- **Nano-materials** will be stronger, lighter, more or less abrasive as required, and
- **Nano-precision** in machining and sensing will enable improved precision in machinery and processes.

The second stage foresees totally new methods of manufacturing being developed. For example, it is now possible in the laboratory to manipulate single atoms, allowing scientists to build up nano-scale objects at the atomic level. This sort of “bottom-up”

construction is currently extremely laborious, but as techniques develop and become automated, it is predicted that commercial equipment will become available that will enable mass production of specialised nano-components.

Perhaps this will (in the distant future) even lead to the ultimate vision expressed in many science fiction stories, of machines that can take any source material, such as soil or waste, reduce it to its component atoms and reconstruct them into whatever is required – food, machinery, etc.

Food applications

Food is another area likely to see widespread applications of nano-technologies. Key issues in food supply include provenance (verifying where the food comes from), identification (verifying that the label matches what is inside the packet), quality (that the food is not spoiling due to microbial activity) and safety (that the food has not been tampered with).

All the above issues can potentially benefit from nanotechnologies. Nano-biosensors could detect trace elements in the food, and the results then be used to confirm provenance and identity. Packaging materials incorporating sensitive nano-particles could change colour if food starts to go off, or if the packaging has been damaged, thereby alerting consumers to potential tampering.

Water supplies can be safeguarded in a similar fashion – nano-sensors embedded in taps could alert to dangerous levels of chemical contaminants or microbes, and cheap, portable test units could be available for testing water supplies in disaster situations or while travelling.

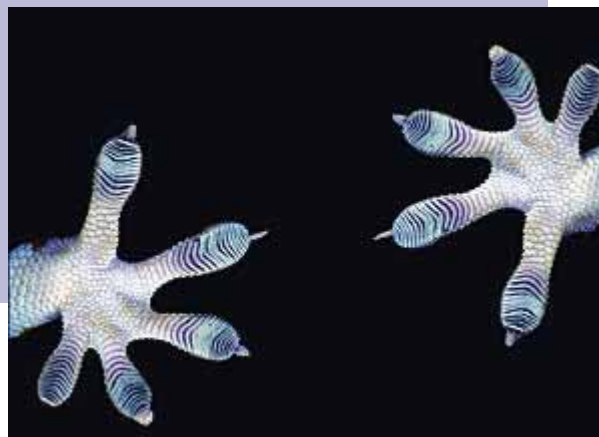
Nano-particles could also play a role in functional foods. In the same way that nano-particles can be used to encapsulate drugs for timed or targeted release, they can also be used to encapsulate nutrients or friendly microbes and then added to foods. In this way the functional elements are protected while passing through the acidic stomach and are released only in the intestinal tract where they do the most good.

APPLICATION EXAMPLE - Adhesives based on geckos feet

The feet of the gecko can cling easily to virtually any surface, and are covered with millions of superfine hairs, each of which branches out again at its end into hundreds of spatula-shaped structures. These adhesive pads measuring only a few nanometers can nestle perfectly into any nanoniche of the contact surface. Weak atomic forces of attraction then come into effect and, when cumulated million-fold, provide a secure foothold for these reptiles which can reach a length of up to forty centimeters.

BASF research scientists are working on simulating it with nanostructured films to produce adhesive tapes that stick without adhesive.

[©Press Photo BASF]



Environmental applications

Many of the technologies described above for food also have applications in dealing with environmental problems.⁶⁰ Thus although some nano-technologies pose environmental concerns (unknown side effects of nano-particles, release of toxic metals into the environment, etc) other nanotechnologies may be highly beneficial to the environment

Miniature sensors will greatly aid efforts to monitor pollution as well as environmental conditions in general. Advances in wireless communications, use of natural power sources and miniaturisation of batteries will in the near future enable sensors to be released into the air and waterways, or be attached to migrating animals, and provide continuous data in a level of detail and coverage not currently possible. Sensors could also be placed around industrial installations, monitoring both production processes thereby improving efficiencies, and also monitoring emissions to ensure compliance with regulations.

Nano-structured filters and catalysts will also provide new methods of removing contaminants from air and water, not only in industrial settings, but also for communal or individual use. This may be particularly important in third world countries where safe drinking water can often be very difficult to provide. In the longer term, such technologies may even provide effective methods of dealing with oil spills, heavy metal contamination and reprocessing of nuclear waste.

Security applications

Many facets of security are expected to be enhanced, in applications ranging from communications to bioterrorism.

Novel detection systems are being developed with a high specificity that provide early warning against biological or chemical agents, ultimately down to the level of single molecules. These could be used to un-intrusively detect drugs, explosives, dangerous chemicals and micro-organisms around travel hubs and other high risk public places.

Miniature cameras and motion detectors that run off solar energy or miniaturised energy sources will make public and private security systems more affordable and easier to manage. It is expected, however, that such applications may raise new issues in relation to the privacy rights of individuals, which may require reviews of existing legislation.

Nano-tagging will provide improved protection of property, both of private objects of high value and public assets such as banknotes. Combined with miniaturised wireless and GPS technologies, such tagging may enable objects to call for help and identify their location if lost or stolen.

New cryptographic techniques for data communication are being developed, including totally new mechanisms using some of the unique quantum effects that exist in nano-structures. These will help provide more reliable and secure systems for financial transactions and private communications..

Military applications

Many of the nanotechnology applications discussed under other headings can be adapted for military use, such as improved energy sources, stronger materials, filters for toxins, medical treatment of wounds, etc.

In addition, however, significant military research funding is focused on nanotechnology solutions for:

Smart weapons: especially miniaturized, robotic weapons and intelligent, target-seeking ammunition;

Nano-sensors: for surveillance and monitoring, detection of hidden explosives, biological and chemical agents;

Nanomaterials: in uniforms and equipment to make them stronger and lighter, thereby reducing the heavy loads currently carried by infantry soldiers while providing better protection;

Performance enhancers: such as artificial blood cells or receptor enhancers that dramatically enhance human performance, increase alertness and reduce reaction times, and

Interfaces: between humans and equipment, such as eye or ear inserts to enable visual and audio communication between soldiers and between soldiers and equipment.

APPENDIX 3: Ethical, legal and social aspects

Extracts from *Nanologue - Opinions on the Ethical, Legal and Social Aspects of Nanotechnologies; Results from a Consultation with Representatives from Research, Business and Civil Society, May 2006*, a report which summarises earlier findings and the outcomes of a series of individual and group interviews involving various target groups, to present an general overview of the concerns society has with nanotechnology.

The authors classify the issues into 3 orders of effect:

First order effects: Impacts and opportunities created directly by the physical properties of nanotechnology components. One example would be the (potential) toxicity of nano-particles.

Second order effects: Impacts and opportunities that derive from applications using nanotechnology-components and/or nanotechnology-based solutions. For example: More mobile power sources due to a higher efficiency of energy conversion or storage due to the use of nano-materials.

Third order effects: Impacts and opportunities created by applications using nanotechnology-components and/or nanotechnology-based solutions that are not genuinely associated with the nanotechnology application but rather with the introduction of a new technology application in general. For example the discussion about a potential divide between those who have access to nanotechnology and those who do not is not unique for nanotechnology, but is symptomatic for new resource and knowledge intensive technologies in general.

The consultations found that “discussing ethical, legal and social issues arising from nanotechnology applications shows that only few issues become matters of concern as an immediate result of the underlying nanotechnology-component. More typically, the ethical, social and legal aspects are associated with specific applications. The research also shows that a significant number of issues are not new or unique to nanotechnologies”.

The following table provides an overview of the benefits and risks of the ethical, social and legal aspects of nanotechnology as identified by participants in the consultations.

Environmental performance	Human Health	Privacy	Access	Acceptance	Liability	Regulation & Conanotechnologyrol
First order effects: Impacts and opportunities created directly by the physical properties of nanotechnology components.						
Eco-, energy-, Resource efficiency gains, e.g. by building materials bottom-up (B) Eco-toxicity of nanoparticles (R) End-of-life treatment of particles unsolved (R)	Toxicity of nanoparticles (R) Evolving of new microbial resistances (R)					
Second order effects: Impacts and opportunities that derive from applications using nanotechnology-components and/or nanotechnology-based solutions.						
Improved performance of environmental echnologies (B) Technological solutions for climate protection, such as improved energy conversion and production (B) Improved water purification technologies (B) Environmental Risk at end of life (R)	Improved diagnostics performance (B) Improved food safety (B) Risks of malfunctions or false handling of nanotechnology-based applications e.g. misinterpretation of testing results in diagnostics (R) Occupational hazards of working with nanotechnology (R)	Increased availability of personal health data e.g. genetic testing results (R)	Cheap, decentralised energy supply (B) Access to improved medical diagnostics (B/R) Technologies too expensive for 3rd world (R)	Improved performance of e.g. nanotechnology-based medical applications or clean energy technologies will help acceptance of nanotechnology (B) Cost savings in health care due to nanotechnology-based diagnosis applications improve acceptance (B) nanotechnology-based risks in applications that don't really benefit society are a risk for acceptance (R)	Is the current liability regime sufficient for nanotechnology applications? Opinions diverge (R/B)	Current regulatory framework largely considered sufficient on general level (B) Adaptation of regulation on a specific application level might be needed (R)

Third order effects: Impacts and opportunities created by applications using nanotechnology-component and/or nanotechnology-based solutions that are not genuinely associated with the nanotechnology-application but rather with the introduction of a new technology application in general.						
Eco-efficiency gains e.g. due to raw-material or energy saving (B) Rebound effects cause increasing demand on resources (R)	Increasing pressure on health care due to toxicity (R) Expensive and knowledge intense applications lead to "health-divide" (R) Shift in the general perception of what can be considered "healthy" through extended monitoring abilities (R)		FTechnology divide within and between societies and countries (R) Limited access to nanotechnology based solutions through IPR (R) Risk transfer to 3rd world countries due to dual standards and regulations (R) Increasing concentration of economic and corporate power (R)	Public perception on and agreement to nanotechnology-based applications including the debate on ethical and social issues (R/B) A nano-hype might lead to public backlash (R)		Lack of sufficient legal framework (R)
(B) = Benefit; (R) = Risk						

APPENDIX 4: Extracts on Health and Safety from EC 2004 Communication

Section 1.3 Which approach should be adopted to ensure that nanotechnology is safe?

In accordance with the Treaty, applications of nanotechnology will need to comply with the requirements for a high level of public health, safety, consumer and environmental protection.⁸ It is important for this rapidly evolving technology to identify and resolve safety concerns (real or perceived) at the earliest possible stage. Successful exploitation of nanotechnologies needs a sound scientific basis for both consumer and commercial confidence. Moreover, all provisions should be taken to ensure health and safety at work.

It is essential that the aspects of risk are addressed upfront as an integral part of the development of these technologies from conception and R&D through to commercial exploitation, in order to ensure the safe development, production, use and disposal of products from nanotechnology. Nanotechnologies present new challenges also for the assessment and the management of risks. It is therefore important that, in parallel with technological development, appropriate R&D is undertaken to provide quantitative data on toxicology and ecotoxicology (including human and environmental dose response and exposure data) to perform risk assessments and, where necessary, to enable risk assessment procedures to be adjusted.

[...]

Section 4. Public health, safety, environmental and consumer protection

More generally, public health, environmental and consumer protection require that those involved in the development of nanotechnologies—including researchers, developers, producers, and distributors—address any potential risk upfront, as early as possible, on the basis of reliable scientific data and analysis, using appropriate methodologies. This presents a challenge since predicting the properties of nanotechnology-based products is difficult because it requires that classical physics and quantum mechanical effects are both taken into account. In many ways, engineering a substance with nanotechnology can be likened to creating a new chemical. As a result, addressing the potential risks of nanotechnologies to public health, the environment and consumers will require evaluating the possible re-use of existing data and generating new, nanotechnology-specific data on toxicology and ecotoxicology (including dose response and exposure data). This also calls for examining and, if required, adjusting risk assessment methods. In practice, addressing the potential risks associated with nanotechnologies necessitates that risk assessment be integrated into every step of the life cycle of nanotechnology-based products.

Actions: Public health, safety, environmental and consumer protection

In support of a high level of public health, safety, environmental and consumer protection,

the Commission highlights the need:

- (a) to identify and address safety concerns (real or perceived) at the earliest possible stage;
- (b) to reinforce support for the integration of health, environmental, risk and other related aspects into R&D activities together with specific studies;
- (c) to support the generation of data on toxicology and ecotoxicology (including dose response data) and evaluate potential human and environmental exposure.

The Commission calls upon the Member States to promote:

- (d) the adjustment, if necessary, of risk assessment procedures to take into account the particular issues associated with nanotechnology applications;
- (e) the integration of assessment of risk to human health, the environment, consumers and workers at all stages of the life cycle of the technology (including conception, R&D, manufacturing, distribution, use, and disposal).

APPENDIX 5: EU Safety Legislation applied to nanotechnology

The EC in its June 2008 Communication **REGULATORY ASPECTS OF NANOMATERIALS** has identified that existing legislation framework, grouped under four categories — **chemicals, worker protection, products and environmental protection** — should be sufficient to regulate the safety of new nano-materials if several aspects of implementation are appropriately modified to cater for nanotechnology.

However the communication stresses that nanotechnology is not expressly defined in most of the identified legislation and that it is therefore up to the relevant authorities to take action to update registers and require additional information from manufacturers that utilise nanotechnologies in order to properly classify their products.

Chemicals

Chemicals are regulated in the EU by REACH, a new EC Regulation on chemicals and their safe use (EC 1907/2006) that entered into force on 1 June 2007.

REACH is based on the principle that manufacturers, importers and downstream users have to ensure that they manufacture, place on the market or use such substances that do not adversely affect human health or the environment. Its provisions are underpinned by the precautionary principle.

Manufacturers and importers are required to gather information on the properties of their chemical substances, thereby facilitating their safe handling, and to register the information in a central database run by the European Chemicals Agency (ECHA) in Helsinki. The database is publicly available for consumers and professionals to access hazard information.

Under REACH, manufacturers and importers will have to submit a registration dossier for substances that they manufacture or import at or above 1 tonne per year. At or above 10 tonnes/year, the registrant will be obliged to produce a chemical safety report. Furthermore, if deemed necessary for the evaluation of the substance the European Chemicals Agency can require any information on the substance, independent of the minimum information requirements of REACH.

When an existing chemical substance, already placed on the market as bulk substance, is introduced on the market in a nanomaterial form (nanoform), the registration dossier will have to be updated to include specific properties of the nanoform of that substance. The additional information, including different classification and labelling of the nanoform and additional risk management measures, will need to be included in the registration dossier. The risk management measures and operational conditions will have to be communicated to the supply chain.

In order to address the specific properties, hazards and risks associated with nanomaterials, additional testing or information may be required.

For substances of very high concern, an authorisation will be required for their use and their placing on the market.

Worker Protection

Framework Directive 89/391/EEC6 places a number of obligations on employers to take measures necessary for the safety and health protection of workers. It applies to all substances and work activities including manufacturing and use of chemicals at all levels of the production process, regardless of the number of workers involved and quantities of materials produced or technologies used.

This Directive fully applies to nanomaterials. Employers, therefore, must carry out a risk assessment and, where a risk is identified, take measures to eliminate this risk.

The Directive foresees the possibility to adopt individual directives laying down more specific provisions with respect to particular aspects of safety and health. As these Directives introduce minimum requirements, national authorities have the possibility to introduce more stringent rules.

Products

Product legislation lays down requirements regarding specific products, such as medicinal products, plant protection products (PPP), cosmetics, food and feed additives, etc. Consumer products that are not governed by specific legislation have to meet the requirements of the General Product Safety Directive.

Where products are subject to a pre-market control or pre-market notification, e.g. medicinal products, novel foods, plant protection products, the assessment and management of risks in relation to nanomaterials can be verified by authorities before placing on the market.

Where products can be placed on the market without specific pre-market procedural requirements (e.g. cosmetics, consumer products subject to the general product safety directive, various products regulated under the New Approach), compliance with legal requirements must be verified at the level of market surveillance.

In order to increase the level of protection, regulatory change has been proposed with respect to cosmetic products, placed on the market without pre-market control. The requirements regarding the risk assessment will be clarified. Further, manufacturers will be obliged to indicate whether their products contain nanomaterials when notifying their placing on the market and to set up a mechanism in order to monitor the health effects

on cosmetic products placed on the market.

Environmental protection

Environmental regulation relevant in this context relates in particular to integrated pollution prevention and control (IPPC), the control of major accident hazards involving dangerous substances (Seveso II), the water framework directive and a number of waste directives.

The IPPC Directive¹⁴ covers approximately 52,000 industrial installations across the EU and requires installations falling under its scope to operate in accordance with permits including emission limit values based on the application of best available techniques (BAT). In principle, the IPPC Directive could be used to control environmental impacts of nanomaterials and nanomaterials issues at IPPC installations through the inclusion of such considerations into the Commission's BAT Reference Document (BREFs) process should the need arise.

The Seveso II Directive applies to establishments where named dangerous substances are present above specific quantities. It imposes a general obligation on operators to take all measures necessary to prevent major accidents and to limit their consequences for man and the environment. If certain nanomaterials are found to demonstrate a major accident hazard, they may be categorised, together with appropriate thresholds, in the context of the Directive.

The Water Framework Directive (2000/60)¹⁶ sets common principles and an overall framework for action to improve the aquatic environment and to progressively reduce the pollution from priority substances and phasing out emissions, discharges and losses of priority hazardous substances to water. A list of 33 priority substances has been established in 2001. Nanomaterials could be included among the Priority Substances depending on their hazardous properties.

Directive 2006/12/EC on waste sets the general framework and imposes an obligation on Member States to ensure that waste treatment does not adversely affect health and the environment. Wastes containing nanomaterials could be classified as hazardous, if the nanomaterial displays relevant properties which render the waste hazardous.

Specific legislation has been adopted to deal with particular waste streams or specific waste treatment processes, such as incineration and landfill. Current EU waste legislation covers general requirements for the protection of health and the environment during waste management. It also includes requirements for the management of specific waste materials that may contain nanomaterials whilst not explicitly addressing the risks of nanomaterials. If the need for more specific provisions is established, appropriate action can be proposed or implemented under the current legislative framework. Similarly, action can be taken by Member States in implementing current provisions in the framework of national policies.

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