# International Strategy and Foresight Report on Nanoscience and Nanotechnology

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**Final Report 19th March 2006**

## Content

# 1 INTRODUCTION INTO NANOTECHNOLOGY

Atoms and molecules are the essential building blocks of all things. The manner in which things are “constructed” with these building blocks is vitally important to their properties and how they interact. Nanotechnology refers to the manipulation or selfassembly of individual atoms, molecules, or molecular clusters into structures to create materials and devices with new or vastly different properties. Nanotechnology can develop new ways to manufacture things. The top down approach entails reducing the size of the smallest structures to the nanoscale and can be clearly seen in nanoelectronics and nanoengineering where photonics is an early application. The bottom up approach involves manipulating individual atoms and molecules into nanostructures and more closely resembles chemistry of biology.

Since the late 90`s, nanotechnology has shot into the limelight as a new field with tremendous promise.[1] Experts have even compared the revolutionary aspects of nanotechnology to silicon and plastic and their impact on society and the wide range of new products, which arose from their use. This new, “small” way of manipulating materials has already led to new research areas and the development of new products, which are available on the commercial market.

## 1.1 History

The roots of modern nanotechnology and nanomaterials are often traced back to a 1959 talk given by Nobel prize winnning physist Dr. Richard Feynman at a meeting of the American Physical Society titled “There’s Plenty of room at the Bottom”. He speculated that future scientists and engineers would build complex structures from atoms and molecules. However, the term „nanotechnology“ was established not until 1974 when the japanese researcher Norio Taniguchi made the distinction between engineering at the micrometer scale and the new field of ultraprecision machining and ultrafine materials processing in the sub-µm range that was beginning to emerge[2]. Nascent nanotechnology began to “grow up” and enter the mainstream consciousness when Gerd Binnig and Heinrich Röhrer (Nobel prize in 1986) at IBM developed the scanning tunneling microscope (STM) in 1981 as one of the first tool not only to investigate but also to manipulate materials on an atomic scale. Tools like scanning probe microscopy (SPM) atomic force microscopy (AFM), near-field microscopy or transmission electron microscopy (TEM) have provided views into the inner workings of atomic bonding, molecular assembly, and the structure of materials at the smallest scale and have taken atomic manipulation out of the chemistry beaker into the realm of engineering.

Another milestone in the history of nanotechnology was the discovery of the Fullerenes or „Buckyballs“, a new nanostructured carbon modification, with work of Curl, Kroto and Smalley in 1985. The study of Fullerenes has led to the discovery of tube-like structures of carbon atoms in 1991 which are basically sheets of graphite rolled up with their edges connected to form a cylinder and for which tremendous application potential in electronics and materials engineering are predicted due to their outstanding properties.

In the 1980‘s the basic ideas of molecular manufacturing surfaced in K. Eric Drexler’s paper, “Protein Design as a Pathway to Molecular Manufacturing”.[3] In his later work, he described possible methods of fabricating devices and structures to complex atomic specifications via the creation of a self-replicating „assembler“. This tool would be a general purpose device for molecular manufacturing, capable of guiding chemical reactions by positioning molecules [4,5]. Although this vision of a universal assembler is very controversial, the aspect of bottom-up technologies for production of nanomaterials has become an important branch in the field of nanotechnology.

In the 1990‘s federal agencies e.g. in the U.S. Europe and Japan began to pursue programs into the various branches of nanotechnology e.g. nanoelectronics, nanomaterials, etc. In the late 1990‘s the perception become accepted, that the field has not to be dealed with as afragmentation of various small-scale sciences, but as different aspects of the same science, nanotechnology. It was persued to bundle the different activities in focused initiatives (e.g. the National Nanotechnology Initiative in the U.S.) and to push forward nanotechnology as an interdisciplinary cross section key technology. Meanwhile nanotechnology is established as aspecific field of public research and development programs in nearly all industrialized countries.

## 1.2 Definitions

Definitions of nanotechnology are not always clear or indeed agreed upon. Also, nanotechnology, in many cases is rather nanoscience in the range of basic research then technology. Nevertheless a general consensus exists that nanotechnology can be characterized as a technology concerned with the production, study and utilization of lateral structures, layers, molecular units, inner boundary layers and surfaces with critical dimensions or production tolerances that extend from about 100 nanometers down to atomic orders of magnitude. But not only geometrical aspects have to be considered when dealing with nanotechnology. One important aspect of nanotechnology is the significant change of material properties and physical phenomena on a nanometer scale. Table 1 summarizes some necessary changes in the perspective of conventional macroscale technologies compared to nanotechnology.

| **Macroscale Technologies** | | **Nanoscale Technologies** |
|---|---|---|
| Classical Continuums Physics | ⇔ | Quantum Physics |
| Solid State Properties | ⇔ | Binding Properties |
| Bulk properties dominating | ⇔ | Surface properties dominating |
| Conventional Materials/Mixtures | ⇔ | New compounds and mixtures |
| Classical Top-Down-Approach | ⇔ | Combination with Selforganisation |
| Statistical Ensembles | ⇔ | Individual particles |
| Sufficient high energy ranges | ⇔ | Energy range of therm. fluctuations |
| Moderate field strength | ⇔ | Extremely high field strength |

Table 1: Necessary changes in the perspective of macroscale technologies compared to nanotechnology.[6]

A further characteristic of nanotechnology is that it represents not an uniform technology platform but a broad conglomerate of different technological and scientific disciplines comprising for example the following subsections:

- Nanostructured Materials
- Nanoelectronics
- Nanophotonics
- Nanobiotechnology
- Nanoanalytics

## 1.3 Production Methods

As mentioned above nanotechnology is applied to very diverse fields of application. For all these fields, techniques and specific instrumentation for fabrication, control and measurement have been developed to achieve control at the nanometer scale. Concerning production methods two main routes can be distinguished:

- **Top-down approach:** Reduction in structur sizes of microscopic elements to te nanometer scale by applying specific machining and etching techniques (e.g lithography, ultraprecise surface figuring)
- **Bottom-up approach:** Controlled assembly of atomic and molecular aggregates into larger systems (e.g., clusters, organic lattices, supramolecular structures and synthesized macromolecules)

### 1.3.1 Top-Down Approach

Top-down techniques take a bulk material and form, structure and modifiy it into the desired product. The motivation for producing smaller and smaller structures is mainly determined by microelectronics, where various sub-µm technology processes are being developed to move into the range of nanoelectronics for the next generations of components. Another important top-down-approach is the surface figuring of ultraprecise components especially in the range of optics e.g. by mechanical or plasma treatment.

Lithography is the key technology to realise very small feature size for nano-components. A variety of lithographical methods exists, which are based on different physical principles and have different characteristics with regard to resolution, velocity, patterning and transfer steps, such as beam lithography techniques (optical, x-ray-, ion beam or electron) or soft lithography techniques (printing, stamping, molding and embossing).

Optical lithography, the main technology used today in the range of microelectronics is based on photochemical patterning of a resist through a mask, followed by chemical etching of exposed areas. The minimum feature sizeaccessible by such a process is determined by the wavelength of the illumination. Optical lithograhpy is predicted to be applicable to feature sizes beyond 100 nm by using ultraviolet wavelength tools (193 nm wavelength resp. 157 nm). The reduction of feature sizes down to 50 nm and below will require more advanced lithography tools. Among different candidates, two technological approaches are particularly interesting for nanotechnology.

- Extreme Ultraviolet Lithography.

As the candidate for the next generation for the microelectronics industry, this activity is strongly supported by industrial consortia and public funding programmes. EUV lithography, at the wavelength of 13nm, will achieve feature size at 45 nm and below. More intensive research efforts are required at the academic and institutional level to ramp up the general state of all process elements.

- Nanoimprint

Soft lithography techniques such as nanoimprint belong to the cheapest and fastest nanolithography techniques available for laboratories. A stamp consisting of an elastomer is covered by an ink, which is able to form a self-assembled monolayer after being printed on the substrate. This monolayer then serves as a mask for further processing by etching or surface reaction.. The stamp itself is cast from a mould patterned lithographicaly, and by using high-resolution techniques such as electron-beam etching it can be given features as small as 10 nm.

### 1.3.2 Bottom-up Approch

Another important route of nanotechnology is the specific assembly of atomic or molecular aggregates into larger systems. Mainly, this uses the principles of self-organization, organic/inorganic boundary surfaces and selective chemical or physical coupling of molecule systems to prepared surfaces. Numerous biological supramolecular structures arise from such spontaneous self-structuring, including double helices, protein coatings and multi-protein complexes. "Programmable" molecular and supramolecular systems of this kind are of significance for making possible highly selective functions such as recognition processes, signal transfer or generation of structures. By using the most diverse recognition units, it should be possible to form numerous structures, shapes and patterns with nanometer dimensions (bands, rings, cylinders, films, strips etc.). Therefore, processes guided by molecular recognition are of particular importance as an approach to the controlled structuring of solid bodies.

In the technical world numerous techniques based on self-assembly have been developed, which can be applied in gas phase, liquid phase or in vacuum, to form nanostructured layers or clusters. Some of the main routes comprise Self-assembled Monolayers (SAM), wet chemical synthesis and gas phase or vacuum depositon methods.

- Self-assembled monolayers

Self-assembled monolayers are produced when a substrate, for example a metallic or porous surface, is placed in contact with a solution of organic molecules, which then spontaneously align themselves with respect to the substrate. The coated material can then in turn be the substrate for a layer of a different compound.

- Wet chemical synthesis

There are several wet chemical methods which can be used for producing nanomaterials, such as so-gel-processing or precipitation methods, where nanoparticles are generated by a special treatment of precursor materials in solutions or colloids. The nanoparticles can be seperated and processed to form nanopowders or nanocoatings with special properties.

- Deposition methods

Classical deposition techniques, which are quite established since a while, can be used to make nanoscale films, nanoparticles, nanotubes or other structures and find broad applications in the range of nanotechnology. The main classes of deposition methods are CVD (Chemical Vapor Deposition) methods, starting from gaseous precursors, and PVD methods, starting from a solid target material, which is evaporized by physical treatments. Both methods have a great variation range concerning procesing parameters and substances. For a better control of nanostructure growth, these techniques are often combined with top-down lithography methods for a specific functionalization and conditioning of the substrate.

## 1.4 Disciplines

### 1.4.1 Nanostructured Materials

The physical and chemical properties of nanostructured materials (such as optical absorption and fluorescence, melting point, catalytic activity, magnetism, electric and thermal conductivity etc.) typically differ significantly from the corresponding coarser bulk material. Nanostructured materials can be classified with regard to the dimensionality of the nanostructure into nanoparticles (nanoscale in 3 dimensions) nanowires/-tubes (nanoscale in 2 dimensions), nanolayers (nanoscale in 1 dimension) or nanoporous materials.

- Nanoparticles

Nanoparticles are constituted of several tens or hundreds of atoms or molecules and can have a variety of sizes and morphologies (amorphous, cristalline, spherical, needles etc.). Some kind of nanoparticles are already available commercially in the form of dry powders or liquid dispersions. The latter is obtained by combining nanoparticles with an aqueous or organic liquid to form a suspension or paste. It may be necessary to use chemical additives (surfactants, dispersants) to obtain a uniform and stable dispersion of particles. With further processing steps, nanostructured powders and dispersions can be used to fabricate coatings, components or devices that may or may not retain the nanostructure of the particulate raw materials. Currently, the most commercially important nanoparticulate materials are metal oxides, such as silica ($SiO_2$), titania ($TiO_2$), alumina ($Al_2O_3$), iron oxide ($Fe_3O_4$, $Fe_2O_3$). But also carbon nanoparticles like carbon black or fullerenes, compound semiconductor particles like cadmium telluride (CdTe) or gallium arsenide (GaAs) and also metal nanoparticles (especially precious metals such as Ag, Au) find increasing applications.

Also the range of macromolecular chemistry with molecule sizes in the range of up to a few tens of nanometers is often referrred to as nanotechnology. Some compound classes with a special interest in the range of nanotechnology are fullerenes or dendrimers (tree-like molecules with defined cavities), which may find aplication for example as drug carriers in medicine.

Table 2 gives an overview on potential applications of nanoparticles in different industrial branches:[7]

| *Electronic, optoelectronic magnetic applications* | *Biomedical, pharmaceutical cosmetic applications* | *Energy, catalytic structural applications* |
|---|---|---|
| • Chemical–mechanical polishing<br>• Electroconductive coatings<br>• Magnetic fluid seals<br>• Magnetic-recording media<br>• Multilayer ceramic capacitors<br>• Optical fibers<br>• Phosphors<br>• Quantum optical devices | • Antimicrobials<br>• Biodetection and labeling<br>• Biomagnetic separations<br>• Drug delivery<br>• MRI contrast agents<br>• Orthopedics and implants<br>• Sunscreens<br>• Thermal spray coatings | • Automotive catalyst<br>• Ceramic membranes<br>• Fuel cells<br>• Photocatalysts<br>• Propellants<br>• Scratch-resistant coatings<br>• Structural ceramics<br>• Solar cells |

Table 2: Current and emerging applications of nanoparticles (Source: Business Communication Corporation)

- Nanowires and -tubes

Linear nanostructures such as nanowires, nanotubes or nanorods can be generated from different material classes e.g. metals, semiconductors or carbon by means of several production techniques. As one of the most promising linear nanostructures carbon nanotubes can be mentioned, which can occur in a variety of modifications (e.g. single- or multiwalled, filled or surface modified). Carbon Nanotubes are expected to find broad application in nanoelectronics (logics, data storag or wiring, as well as cold electron sources for flat panel displays and microwave amplifiers) and also as fillers for nanocomposites for materials with special properties. Carbon nanotubes can be produced meanwhile in a tons-scale by means of CVD methods and therefore may be become available at reasonable prices in the near future.

- Nanolayers

Nanolayers are one of the most important topic within the range of nanotechnology. Through nanoscale engineering of surfaces and layers a vast range of functionalities and new physical effects (e.g. magnetoelectronic or optical) can be achieved. Furthermore a nanoscale design of surfaces and layers is often necessary to optimize the interfaces between different material classes (e.g. compound semiconductors on silicon wafers) and to obtain the desired special properties. Some application ranges of nanolayers and coatings are summarized in table 3.

| Surface Properties | Application examples |
|---|---|
| • Mechanical properties (e.g. tribology, hardness, sratch-resistance) | Wear protection of machinery and equipment, mechanical protection of soft materials (polymers, wood, textiles etc.) |
| • Wetting properties (e.g. antiadhesive, hydrophobic, hydrophilic) | Antigraffiti, Antifouling, Lotus-effect, self-cleaning surface for textiles and ceramics etc. |
| • Thermal and chemical properties (e.g. heat resistance and insulation, corrosion resistance) | Corrosion protection for machinery and equipment, heat resistance for turbines and engines, thermal insulation equipment and building materials etc. |
| • Biological properties (biocompatibility, anti-infective) | biocompatible implants, abacterial medical tools and wound dressings etc. |
| • electronical and magnetic properties (e.g. magneto-resistance, dielectric) | Ultrathin dielectrics for field-effect transistors, magnetoresistive sensors and data memory etc. |
| • Optical properties (e.g. anti-reflection, photo- and electrochromatic) | Photo- and electrochromic windows, antireflective screens and solar cells etc. |

Table 3: Tunable properties by nanoscale surface design and their application potentials

- Nanopores

Materials with defined pore-sizes in the nanometer range are of special interest for a broade range of industrial applications because of their special properties with regard to thermal insulation, controllable material seperation and release as well as templates or fillers for chemistry and catalysis. To mention here are for example aerogels, which are ultralight nanoporous materials produced by sol-gel chemistry. A vast range of application potentials can be stated for these nanomaterials such as catalysis, thermal insulation, electrode materials, environmental filters and membranes as well as controlled release drug carriers.

### 1.4.2 Nanoelectronics

In the last four decades the power of computer chips has steadily increased according to the so called Moore’s law predicting that the number of transistors that the industry would be able to place on a single chip would double every two years. In the near future the feature sizes of high-end computer chips will pass the 100 nm border reaching the realm of nanoelectronics. Conventional CMOS electronics will soon reach economical (costs of chip factories) and physical (e.g. quantum effects) limits. Nanoelectronic technologies here are expected to provide the basis for continued scaling of Moores law into the next decade, as well as providing the potential for new sensing applications and hybrid architectures combined with traditional electronics. Nanoelectronic technologies include (but are not limited to) ultra-scaled silicon FETs, single electron devices, spintronics, quantum information devices, molecular electronic devices and polymer electronics.

- Ultra-scaled silicon FETs

According to the semiconductor industry roadmap the feature sizes of silicon computer chips will soon shrink to lower than 100 nm. To reach the goal of further shrinking feature sizes new production methods have to be established such as EUV-lithography (see chapter 1.3.1) and a lot of technical and economical barriers have to be overcomed.[8]

- Single electron devices

Single electron transistors (SETs) are often discussed as elements of nanometer scale electronic circuits because they can be made very small and they can detect the motion of individual electrons. However, SETs have low voltage gain, high output impedances, and are sensitive to random background charges. This makes it unlikely that single-electron transistors would ever replace field-effect transistors in applications where large voltage gain or low output impedance is necessary. The most promising applications for SET‘s are charge-sensing applications such as the readout of few electron memories, the readout of charge-coupled devices, and precision charge measurements in metrology.

- Spintronics

Spintronic components utilize not only the charge but also the magnetic moment of the electron for data processing or storing. There are already forecasts according to which components that only switch the spin of electrons could be clearly faster than those which function on the basis of electrical charge. Additionally the switching process would need less energy than a comparable charge transfer. Spintronic can path the way for programmable logics and has already entered the commercial market in the data storage sector. As one of the first components, which uses the electron spin, the „spin valve“ read head in hard disk drives, based on the GMR effect has already successfully been developed into a mass product. A further much promising candidate for future spintronic elements in the range of data storage is the MRAM (Magnetic Random Access Memory) as an alternative to DRAM or Flash memory.

- Quantum information devices

In conventional components, quantum effects emerge as disturbing influences on the nanoscale, which impair the function of the element. Quantum information processing on the opposite side is based on the specific utilization of quantum effects for a completely new form of highly parallel data processing. Quantum information processing has the potential to realize ultrafast algorithms or secure data transfer. Realizations of elemental circuits and functions of these computers are investigated based on semiconductor as well as on superconductor nanostructures. However, there many obstacles to realize a quantum computer that could rival today‘s modern digital computer. Among these difficulties, error correction, decoherence, and hardware architecture are probably the most formidable.

- Molecular electronics

In molecular electronics, organic and/or biological molecules build the structure for the realization of electronic functions and/or elements. Fundamental questions within this research field are in particular the reversibility of switching processes, the switching speed, the scaling up to large molecular circuits, the design of appropriate processors and their interfaces to the macroscopic world. For the production of molecular circuits in particular, methods of self-organization are considered, which should allow a costadvantageous production. The area of molecular electronics is at present still in the stage of basic research and far from market readiness. Research approaches aiming at the realization of molecular computer architectures are for example based on carbon nanotubes or DNA molecules.

- Polymer electronics

In the last years fast progress has been made in developing organic materials like polymers and other makromolecules which exhibit excellent electronic performance making them applicable for electronic devices including transistors, light emitters, photo diodes and displays. Although polymer electronics have lower performances than CMOS electronics they will find applications in low-cost, large area electronics on flexible substrates such as flexible displays (OLED) or identification tags.

### 1.4.3 Nanophotonics

Diffractive optical elements, optoelectronic transducers and photonic components, which play an important role in optical data communication, can be substantially improved through nanotechnology. Nanostructured photonic components (e.g. quantum well or quantum dot lasers, photonic crystals) offer large market potentials in the future in the range of optical data communication or consumer electronics (laser television, displays).

- Photonic crystals

Photonic crystals exhibit a periodic refractive index and possess an analogy to semiconductors in electronics, a "photonic band gap" for certain frequency in the visible and IR wavelength ranges. The main research areas include microlasers, compact splitters, dispersion compensating elements, etc. At present, intensified efforts are made for the development of three-dimensional photonic crystals by utilization of lithography and self-organization procedures. Three-dimensional photonic crystals would open up new possibilities in optical data communication (light could be guided and branched to arbitrary directions) and offer in principle the potential for the realization of purely optical circuits (optical computing). Such photonic transistors are however at present still very far from realization[9].

- Quantum dot devices

Semiconductor quantum dots, which can be manufactured since some years in high quality by means of self organization, offer a new degree of freedom in selecting the working wavelength of photonic elements. They allow to cover almost completely the entire spectral region from the ultraviolet to the far infrared with a small number of substrate materials. Quantum dot based materials are currently under investigation for applications in detectors as well as in light emitters (lasers). Due to the wide tunability of the electronic states of the dots via their sizes materials can be made available which are tailored for a specific application. Quantum dots are also key elements in qualitatively new devices like single photon sources, which are investigated as light sources for quantum information processing.

### 1.4.4 Nanobiotechnology

There are two main research approaches in the range of nanobiotechnology:

- „Nano2Bio" designates the use of nanotechnological tools to study the molecular mechanisms behind various biological processes at the single molecule level. From this perspective, nanoanalysis, nanomanipulation techniques for biological structures and objects, nanotechnologically produced active ingredients for living organisms, nanocarriers for transporting active ingredients, nanomachines, nanobots for research, diagnostics and therapy, nanotechnologically coated implants and nanoelectronic (particularly neurological) implants are possible applications.
- "Bio2Nano" refers to bio(techno)logical materials and designs for producing technical nanosystems. These could be exploited in information and communication, energy, environment and many other areas for technical applications. These include e.g. nanotechnology applications based on biological paradigms (biomimetics), the use of biological components on the nanometer scale for technical systems, or nanoelectronics and nanoinformatics using biological components, functional or organisational principles.

One of the first nanobiotechnologies in the market is micro chips for DNA or protein sequencing (bio-chips). This technology is a good example of how a technology issued from traditional microelectronic industry is combined to a recently developed biotechnology. The economic and social impact of such biological chips is enormous. Another technology under development concerns microfluidic bio-chips, also known as lab-on-a-chip devices. They are all based on manipulation of minute bio-objects immersed in fluids, allowing a on-chip biochemical processing (sampling, mixing, amplification, separation, detection and analysis). A relevant example is the micro channel-based serial assays for DNA. The application area of biochips and microfluidic chips is very broad, ranging from high throughput screening, cell analysis, drug discovery to portable devices for minimal-invasive therapy, precision surgery as well as drug delivery.

### 1.4.5 Nanoanalytics

The characterisation of materials, structures and surfaces with nanoscale respectively atomic resolution is a basic prerequisite for nanotechnological developments and is therefore of central importance for the technology field. A considerable arsenal of high performance measuring techniques exists in the field of nanoanalytics, some of which have already been established a long time ago. These methods work for example with electron-, ion or photon beams, field emission or tunneling effects or are based on electrical, optical, thermal, acoustic or magnetic principles. Analytical procedures on the nanoscale concern the determination of structures, surfaces and thin films as well as physical and chemical material properties. One of the most important tools for nanoanalytics is the Scanning Probe Microscopy (SPM). Scanning probe methods are based on a local reciprocation between a surface and a scanning probe tip, which is brought very near (in atomic dimensions) to the surface of the sample. The measuring procedure can be compared in principle with a miniaturized record player, where a tip moves over a surface, scans it on an atomic scale and converts the signals into an image.

The received information can concern for example the chemical composition of the surface, the distribution of surface potentials, magnetic or electrical fields.

# 2 OPPORTUNITIES IN INDUSTRIAL SECTORS

## 2.1 Information and Communication

The modern information society induces an increasing demand for mobile, powerful and robust information-processing devices with faster transfer and processing speeds, higher storage densities and flexible, integrateable displays. For the future a vision of ubiquitous computing can be described where inexpensive and powerful handheld computing devices connected to a broad band network using wireless technology will be available to all people.

Nanotechnology will be the key for future information and communication technologies. Some of the relevant components and applications are described briefly in the following.

- Data processing and storage

Nanotechnology offers the potential for the production of ultrahigh integrated logics, miniaturized mass memories with extremely high storage density and new non volatile high performance working memories for computer systems. The most relevant technological approaches for the realization of such nanoelectronic devices have already been described briefly in chapter 1.4.2. There are quite a lot of concepts for nanotechnological data memories, which are expected to enter the market in the future. To mention here are MRAMs, based on magentoresistive effects, which possess a high market potential as replacement for DRAM memories because of their special characteristics such as non volatileness of the data (data remain preserved also in case of a power failure and the booting process of computers will become unnecessary) and a low energy consumption. IBM is developing an AFM-based memory, the so called „Millipede“, which is a micromechanical device with an array of nanoscale read/write/erase tips based on scanning probe technology. This device has the potential for a nonvolatile, low power and large capacity data memory (up to 1 Tbit per square inch, which is more than hundred times better than current DVD technology). Also in development are data memories based on phase-change materials, biological molecules or quantum dots.

- Displays

The future demand for full-color, full-motion, energy-efficient and more versatile displays will grow with the ubiquitous dissemination of cell phones, PDAs, e-books and other elctronic devices. These displays should be low in cost, consume minimal power, thin and lightweight and can mount on a flexible substrate. Such flexible displays would not only lead to more economical production processes but also enable future application as head-mounted or head-up displays integrated in goggles, windsreens and other items. There are some nanotechnological flat-panel display technologies that exhibit great promise such as organic light-emitting diodes (OLED) or Field emmission

Displays based on carbon nanotubes (CNT-FED). For both display types a big market potential is predicted if existing technological problems can be solved.

- Mobile electronics

Mobile electronics will become more and more important in the future. The scenario for future applications of mobile electronics includes wearable electronics (woven in textile fibres) for health monitoring or telecommunication purposes, augmented or virtual reality devices in the workplace or for entertainment as well as multifunctional handheld devices with multiple use as a personal electronic butler, simultaneous translator, walking library etc.

The incorporation of new audio, image, video, data input, and wireless capabilities in mobile equipment is leading to new demands and requirements for Power ICs to support these subsystems. As processor speeds increase, power-management chips and subsystems must be built to cope with novel electrical environments and to adjust processor speed in line with the needs of portable applications. New and miniaturized powering devices will be necessary to support these mobile electronics. Nanotechnology can significantly improve mobile energy production in the range of batteries, miniature fuel cells, thermoelectric converters or solar cells.

## 2.2 Chemistry

In the chemical industry nanostructured materials and nanotechnological production processes have already found entrance since a while. Some products based on chemical nanotechnology are already in the market such as nanoparticle based sunsreens, self-cleaning paintings and ceramics („lotus-effect“), nanoparticle as markers in Biochips, fillers in car tyres or catalysts. In principle there is a broad application range for chemical nanotechnology products, but  the most crucial point for commercialization is to demonstrate a better price-performance ratio than conventionell materials and the suitability for real-world application in mass production.  Nanomaterials will only find application in niche markets, if they can not be produced in high volume and at competitive costs. Table 4 gives an overview on existing and potential applications of nanomaterials in different stages of the value chain.

In long run chemical nanotechnology is expected to move far beyond just improving conventional materials. One of the visionary goals of molecular nanotechnology here is to produce „intelligent" materials with intrinsic sensing and acting properties, programmable optical, thermal and mechanical characteristics or even self-healing properties. One objective here is the combination of synthetic and biological materials, architectures and systems, respectively, the imitation of biological processes for technological applications. This field of nanobiotechnology is at present still in the state of basic research, but is regarded as one of the most promising research fields for the future (European Commission 2001)[10] .

| Basic products | Intermediates | Applications |
|---|---|---|
| **Inorganic nanoparticles**<br>metal oxides, nanoclays, metals, fullerenes, carbon black<br>**Organic nanoparticles**<br>polymer dispersions, drugs, dyes, macromolecules (dendri-mers etc.)<br>**Nanoporous materials**<br>aerogeles, zeolites, etc.<br>**Nanocomposites**<br>ceramics, metals/alloys, polymers, functionalised nanoparticles, organic semiconductors, ferrofluids, etc. | • catalysts<br>• membranes and filters<br>• pigments and paints<br>• abrasives<br>• fillers<br>• drugs and drug carriers<br>• foils<br>• testil fibers<br>• markers<br>• superconductors<br>• gas storage<br>• packaging<br>• coatings<br>• thermoelectrics<br>• conductive polymers<br>• organic semiconductors | **Medicine**<br>drug delivery, biochips, implants, antimicrobials<br>**Cosmetics**<br>sunsreens, lip sticks, tooth pastes<br>**Automobile**<br>tyres, construction materials, catalysts, windscreen, fuel cells<br>**Information Technology**<br>data storag, displays, laser-diodes, glas fibers<br>**Energy**<br>solar cells, batteries, fuel cells, capacitors |

Table 4: Existing and potential applications of nanomaterials in different stages of the value chain (Source: VDI-TZ)

## 2.3 Automotive

Certain characteristics of the automotive industry make it a fertile market for the introduction of nanotechnology. The market is very large, has relativ short innovation cycles, is subject to market and regulatory pressure in terms of fuel economy and safety and is also quite heavily influenced by fashions subject to consumer pressures. These are all factors encouraging the introduction of novel technologies. In future automotive engineering, nanotechnological competence will be one of the core capabilities required for this industry to remain internationally competitive. The spectrum of nanotechnological innovation efforts in automotive engineering ranges from components already in use through concrete development activities to ideas with at best long-term potential for realisation. Some of these are fundamentally new developments with far-reaching impacts on the product. Spinoff effects are expected in many other industries.

Nanotechnological developments can play a role in all automotive subsystems and components. Examples include:

- nanoparticles as a filler in car tyres (realised, further development)
- antireflective coatings for displays and mirrors (realised)
- nanoparticle-reinforced polymers and metals (development phase, partly realised)
- nanotechnologically modified adhesive technologies and adhesive primers (in development)
- Improved fuel cell technology and hydrogen storage (research stage)
- sensors (e.g. magnetorestive sensors) and electronic components (e.g. head-up displays, bord computers) based on nanoelectronics (research stage)
- catalytic nanoparticles as a fuel additive (research stage)

- hydrophile surface coatings as anti-fogging coatings for mirrors and screens (research stage)
- carbon nanotube composites for ultra-lightweight car structures (long term)
- "self-healing" coatings, e.g. through self-organisation (long-term at best).

## 2.4 Medicine and Health Care

Healthcare is affected by a large number of social and economic factors. The global healthcare markets are worth several hundred billion euros per year, with pharmaceuticals accounting for the majority of this (approximately $400 billion US in 2002). Nanotechnology is already featuring within the healthcare market as the following examples illustrate:[11]

- Atomic force microscope (AFM) technology (which can move single atoms about) is being used to create smaller and more sensitive microarrays for use in diagnostics and drug discovery. AFMs can also be used to nanostructure surfaces, and for example make them more biocompatible.
- Nanoparticles such as fullerenes, dendrimers, and quantum dots (complexes of semi-conductor material that have unique fluorescent properties) are being exploited in many areas including imaging (e.g. enhancement of magnetic resonance imaging [MRI] and ultrasound) and drug delivery (e.g. a modified fullerene is entering clinical trials as an anti-HIV agent). Formulating drugs with nanoparticles can also improve their solubility (many drugs are not marketed because they are not very water-soluble), increase their resistance to stomach acid and enzymes (allowing better uptake from the small intestine), and allow controlled release (e.g. over days rather than minutes and hours). Nanotubes represent another mechanism for drug delivery, both as a “container” and potentially a system for “nano-injection” into cells.
- In hyperthermic therapy, magnetic particles are covered with biological species and injected into cancerous areas. The molecular structure of the coating forces the cancer cells to absorb the particles, while the healthy cells do not. Using an external magnetic field, the particles are then activated, causing the cancer cells to heat up and die. This is one of the more promising treatments for cancer diseases over the next few decades.
- Nanocomposites of titanium alloys, for example, can be used to improve the biocompatibility and longevity of surgical devices and implants.
- Nanostructuring surfaces can improve cellular attachment (e.g. etching surfaces with nanoscale grooves or using instruments such as an AFM to imprint surfaces with cell attachment molecules), and direct cells to grow into defined structures. By incorporating biodegradable polymers to act as a scaffolding, these structures can be assembled into 3-dimensional “tissues”. Nanostructuring can also be used to provide an anti-microbial coating on implants.

- Antimicrobial agents based on nanomaterials (e.g. silver incorporated into polymer tubes or titanium dioxide coated surfaces) to sterilise medical equipment or other items.

New medical treatments are expected over the medium time scale, eg selforganizing hollow spheres that will transport drugs in the bloodstream to a specific area of the body. Molecular-sized containers or 'cage compounds' (e.g. fullerenes or dendrimers) will also be important for drug-carrying and targeting purposes. External control may even be possible via an additional coupling of magnetic particles or antibodies. Drugs that are presently injected, such as insulin or sera, may be taken orally with the aid of nanomaterials. The potential of such nanoscale drug delivery systems is estimated at $50 million by 2007.[12]

In the long run nanotechnologies will allow us to rapidly sequence an individual's DNA (nanosequencing) and thereby determine genetic susceptibility to disease, drug intolerances and drug metabolism rates (all of which comes under the area of pharmacogenomics). We will be able to target molecules to individual cells within the body for drug delivery or imaging purposes. Patient illnesses will be diagnosed more rapidly through advancements in lab-on-a-chip devices, and at the same time a patient's vital signs could be monitored more closely through similar devices. Damaged body parts could be replaced through advances in tissue engineering (with physiological tissues and organs grown in the clinic in bioreactors) and improved implants will allow patients to regain sight and hearing. Even more visionary is the approach to use nanotechnologies for improving human performance by advanced human-machine-interfaces, artificials limbs, neuro-coupling with electronics etc., which is persued especially in the United States.[13] Examples of payoffs may include improving work efficiency and learning, enhancing individual sensory and cognitive capabilities, revolutionary changes in healthcare, improving both individual and group creativity as well as highly effective communication techniques including brain-to-brain interaction.

## 2.5 Energy and Environment

Energy research is becoming increasingly important, particularly as regards the role it plays in support of a wide range of key EU policies (e.g. security and diversification of energy supply, combating climate change and air pollution, energy market liberalization, sustainable development, industrial competitiveness, regional development and cohesion…). Nanotechnology shows promising potential in all segments of the energy sector: production, storage, distribution and use with the potential to change the way we convert, store and utilize the world's energy supply.

- Energy Production

Nanotechnology offers most promises for renewable energy technologies. On the one hand, the precise control of matter at atomic and molecular level is a requirement for renewables such as cost effective solar PV, which can be made cheaper with a thin layer of active material on a cheap substrate such as plastic, which is much cheaper and more lightweight then glass. Glass is the cost-limiting factor in PV and therefore with glass it will not really be possible to make a great PV breakthrough or be cost competitive. For example, building solar cells containing nanolayers or nanorods could significantly increase the amount of electricity converted from sunlight by using nanostructured surfaces as more effective light absorbers (variation of the absorbing wavelengths by quantum dots) and nano porous electrodes. These same nanomaterials are combined with plastic electronics to develop semiconductor polymer photovoltaics and they are especially advantages for their lightweight and flexible properties. Fuel cells benefits from electrodes and electrolytes with nanostructured and therefore enlarged surface of thin films of nanometer thickness.

- Energy Storage

Nanotechnology applications for energy storage include using nanoparticles and nanotubes for batteries and fuel cells. Nanotechnology is being used to better the performance of rechargeable batteries specifically through the study of molecular electrochemical behaviour. Newly patented lithium ion batteries which use nanosized lithium titanate can provide 10-100 times greater charging/discharging rates, in comparison with the current conventional batteries. Several groups are working on hydrogen storage possibilities in nanostructured materials (like carbon nanotubes, nanocrystalline magnesium compounds or organometalic compounds, which could be applied to the fuel cell sector.

- Environmental Benefits

Nanoparticles can make metals lighter, stronger and harder, better ceramics formability and ductility properties. As a direct result, these same materials can reduce energy, fuel and materials. In mechanical systems much of the energy is required to overcome friction between surfaces. The use of nanoscale lubricants and high-precision surface engineering on a nanometer scale should substantially reduce the energy requirements. Reduction of the material content of products is a key issue for sustainability. Trends in nanotechnology will contribute to cleaner industrial production processes or products, mainly through reducing the use of raw materials and energy. Nanotechnology in conjunction with biotechnology and new materials research can help develop products that require less energy to recycle and produce.

## 2.6 Food sector

Nanotechnology also has applications in the food sector. Many vitamins and their precursors, such as carotinoids, are insoluble in water. However, when skillfully produced and formulated as nanoparticles, these substances can easily be mixed with cold water, and their bioavailability in the human body also increases. Many lemonades and fruit juices contain these specially formulated additives, which often also provide an attractive color. The world market potential of such micronized compounds is estimated at 1 billion $[14] (BASF 2002). Another nanotechnology application in the food sector are packaging materials. To be mentioned here are nanoparticle reinforced polymers with a low gas permeability that can keep food fresh for a longer time. Also inner and outer wall coating technologies are used for improving the gas denseness of PET bottles e.g. by applying plasma methods. In the future also bio and gas sensors could gain importance in the food sector. These sensors could be integrated into packaging materials to monitor the freshness of the food. Spoiling of the food could be indicated by a color change of the sensor. Several concepts have already been developed for such applications based e.g. on silicon or polymer thin film sensors.

## 2.7 Market Assessment

Market assessment for the nanotechnology sector is a difficult task, because there is no generally accepted definition of nanotechnology and it is a very broad area comprising multiple technological fields and branches. In addition, many of the nanotechnology areas are at a very early stage of development, which makes an assessment of future market potentials very difficult. Nonetheless there are some market studies available and table 5 summarizes some figures for nanotechnology products which are most relevant with regard to their market impact for the near future.

| **Products** | **2002** | **2006** |
|---|---|---|
| **Nanomaterials** | | |
| Nanosized Particles | 0,5 | 0,9 |
| Carbon Nanotubes | 0,01 | 1,2 |
| Polymer Nanocomposites | 0,01 | 1,1 |
| Dyes and Pigments | 12,0 | 15,0 |
| Carbon Black | 7,0 | 8,0 |
| **Nanotools** | | |
| Mask Making Lithography | 0,5 | 0,9 |
| Steppers | 5,3 | 7,7 |
| SEM | 0,5 | 0,6 |
| CVD | 3,6 | 5,7 |
| **Nanodevices** | | |
| GMR Hard Disks | 21,8 | 26,9 |
| Laser Diodes | 4,7 | 7,9 |
| OLEDs | 0,1 | 2,5 |
| Field Emission Displays | 0,01 | 0,05 |
| **Nanobiotech** | | |
| DNA Chips | 1,0 | 1,9 |
| Protein Chips | 0,1 | 0,4 |
| Drug Delivery | 0,01 | 0,03 |

Tabelle 5: World markets of nanotechnology products in $US billion per year[15, 16]

# 3 INTERNATIONAL NETWORKS, STRATEGIES AND FORESIGHT

Nanotechnology meanwhile is established as an individual field of public research and development programs in nearly all industrialized states. The strongly increasing public funding for nanotechnology exceeded the sum of 3 billion $ in the year 2003. The leading nations with regard to public nanotechnology funding are Japan (approx. 800

million $ funds in 2003) and the USA (approx. 774 million $ in 2003) followed by Western Europe (approx. 650 million $ in 2003).[17] Also other industrial countries particularly the Southeast Asiatic area (Taiwan, Singapore, South Korea, China) intensify their research efforts in the field of nanotechnology.

Figure 1 shows the world-wide development of public nanotechnology funding from 1997 to 2003. Remarkable is the strong rise in the section „other states“, which relates to Australia, Canada, China, Eastern Europe, Russia, Israel, Korea, Singapore and Taiwan. The Western European funding, from which the portion of Germany constitutes approx. 50 %, was in 1997 approximately on the same level as Japan and the USA. This dropped back since then however. After only a small rise of the European funds in the year 2001 however, a substantial growth of up to approx. 650 million Euro is expected for the year 2003. It has also to be taken into account that the european funding figures are not directly comparable to other countries, because of different funding schemes for the research infrastructure. The European Nanobusiness Association for examples states, that the european nanotechnology funding budget might be even higher than the US budget in 2003, if all relevant funding measures are included in the calculation.[18]

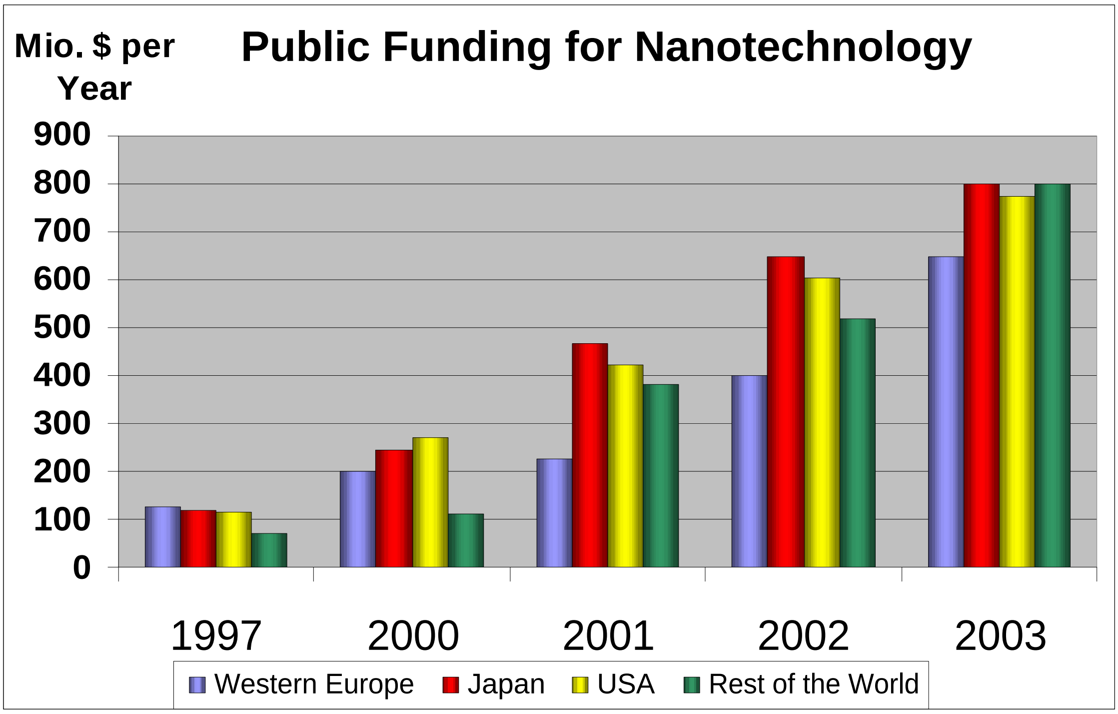


Figure 1: International Comparison of Government Nanotechnology Funding, Source: National Science Foundation 2003

## 3.1 United States

The USA have a leading role in the range of nanotechnology and occupy the second position regarding the public research funding in nanotechnology scarcely behind Japan.

In the USA the Nanotechnology Initiative was established in the year 2000 (NNI[1]), aiming at the promotion of nanotechnology as an urgent national task. The largest portion of funding is attributable to the National Science Foundation (NSF) as well as the ministries for defense (DOD) and for energy (DOE), besides another 7 ministries having their own nanotechnology budget. More than 100 nanotechnology research centers were established in nearly all larger scientific-technological universities and partly also within the non-university range. In some research fields public-private partnerships exist e.g. the SEMATEC consortium within the field of micro/nano-electronics, which is supported by the DARPA and substantial factoring of industrial enterprises (see National Research Council 2002). Several US-American enterprises such as IBM, Hewlett-Packard or Motorola possess their own nanotechnological research centers, which are partly cooperating closely with universities. Beyond that, a multiplicity of smaller enterprises have been founded in the context of public funded programmes, which are specialised in distinct nanotechnology areas.

The scope of public funded nanotechnology programmes in the United States is very broad covering the whole range of nanoscience and nanotechnology. Some priority topics are:

- Nanostructure properties: Developing and extendending the understanding of biological, chemical, materials science, electronic, magnetic, optical, and structural properties in nanostructures;
- Synthesis and processing: Enabling the atomic and molecular control of material building blocks and developing engineering tools to provide the means to assemble and utilize these tailored building blocks for new processes and devices in a wide variety of applications. Extending the traditional approaches to patterning and microfabrication to include parallel processing with proximal probes, selfassembling, stamping, and templating. Paying particular attention to the interface with bionanostructures and bio-inspired structures, multifunctional and adaptive nanostructures, scaling approaches, and commercial affordability;
- Characterization and manipulation: Discovering and developing new experimental tools to broaden the capability to measure and control nanostructured matter, including developing new standards of measurement. Paying particular attention to tools capable of measuring/manipulating single macro- and supra-molecules of biological interest;
- Modeling and simulation: Accelerating the application of novel concepts and high-performance computation to the prediction of nanostructured properties, phenomena, and processes;
- Device and system concepts: Stimulating the innovative application of nanostructure properties in ways that might be exploited in new technologies.

**Foresight activities**

[1] See also www.nano.gov

Foresight activities on nanotechnology emerged very early in the United States. One milestone here was the founding of the Foresight Institute by Eric Drexler with the mission to prepare society for anticipated advanced technologies. Since 1989, the Foresight Institute has organized more than 10 conferences on molecular nanotechnology, has published numerous foresight papers and newsletters and carries on some virtual discussion forums on the internet.[2]

On governmental level first foresight activities on nanotechnology started in 1996, when staff members from several agencies decided to meet regularly to discuss their plans and programs in nanoscale science and technology. This group continued informally until September 1998, when it was designated as the Interagency Working Group on Nanotechnology (IWGN) under the National Science and Technology Council (NSTC) . The IWGN sponsored numerous workshops and studies to define the state of the art in nanoscale science and technology and to forecast possible future developments. Two relevant background publications were produced by the group in 1999:

- Nanostructure Science and Technology: A Worldwide Study[19]
- Nanotechnology Research Directions[20]

In August 1999, IGWN completed its first draft of a plan for an initiative in nanoscale science and technology, which has then been established in 2000. In the frame of the NNI several foresight reports have been published, one of the most recent to be mentioned here is the study „Converging Technologies For Improving Human Performance. Nanotechnology, Biotechnology, Information Technology and Cognitive Science“. Nanotechnology here is regarded as one of the four relevant technologies which are expected to have an enormous impact on the future society, e.g. in the following areas:

- Expanding human cognition and communication
- Improving human health and physical capabilities
- Enhancing group and societal outcomes
- National security

Noteworthy are also nanotechnology foresight activites of Non Governmental Organizations (NGO) in particular in North America.[21,22] As one example, the Millennium Project provides an international capacity for early warning and analysis of global long-range issues, opportunities, and strategies. It was initiated by the The Futures Group International, and the United Nations University (UNU). Since 1996 several international delphi surveys have been conducted, to which about 1,500 futurists, scholars, decisionmakers, and business planners from over 50 countries contributed.[23] In the most recent „State-of-the-Future-Report“ of the American Council for the United Nations University the following four scenarios for 2025 concerning the development of future science and technology management and policy were formulated, where nanotechnology plays a significant role:

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[2] www.foresight.org

- Scenario 1: Science and Technology (S&T) Develops a Mind of Its Own

  The rate of scientific discoveries and advanced technological applications exploded. A global science/social feedback system was at work: science made people smarter, and smarter people made better and faster science. Better and faster science opened new doors to discovery, and new doors led to synergies solving problems and creating new opportunities that created new science that made people smarter. S&T moved so fast government and international regulations were left in the dust. Science and technology appeared to be taking on a mind of its own.

- Scenario 2: The World Wakes Up

  The murder of 25 million people in 2021 by a self-proclaimed Agent of God who created the genetically modified Congo virus finally woke the world up to the realization that an individual acting alone could create and use a weapon of mass destruction. This phenomenon became known as SIMAD—Single Individual Massively Destructive. Regulatory agencies and mechanisms were put into place to control the science- and technology-related dangers that became apparent. Education was a big part of the answer, but connecting the educational systems with the security systems was disturbing to some people. Nevertheless, further individual acts of mass destruction were prevented. International and government regulations did manage the S&T enterprise for the public good.

- Scenario 3: Please Turn off the Spigot

  Science was attacked as pompous and self-aggrandizing, as encouraging excesses in consumption, raising false hopes and—worse—unexpected consequences that could destroy us all. Particularly worrisome was accidentally or intentionally released genetically modified organisms and the potential for weapons of mass destruction. The poor were ignored. A science guru arose to galvanize the public. A global commission was established but failed because of corruption. But a new commission with built-in safeguards seemed to be working.

- Scenario 4: Backlash

  Control was low and science moved fast, but negative consequences caused public alarm. The golden age of science was hyped by the media, but it all proved to be a chimera. Some of the most valued discoveries and new capabilities had a downside and surprises abounded. Rogue nations took advantage of some of these shortcomings. The level of concern rose. Mobs protested. Regulation failed. Progress stalled. And corporate (or government) scientists frequently felt pressure from within their organizations. Both corporate and government organizations could not be counted on to self-regulate.

## 3.2 Japan

Japan has meanwhile the world-wide leading position in public funded nanotechnology research. Both in the application orientated and the basic research range, numerous nanotechnology research programmes were established. Two of the most important nanotechnology research institutions in Japan are the „Joint Research Center for Atom

Technology (JRCAT)" and the „Institute for Physical and Chemical Research (RIKEN)“. As central core of the nanotechnology activities in Japan, the Nanotechnology Research Institute (NRI) of the National Institute Advanced Industrial Science and Technology (AIST) has meanwhile been founded. Furthermore, several industrial consortia especially in the range of nanoelectronics exist, which strive for bundled research efforts. In 2000, Japan established Nanotechnology/Materials as one of four priority research areas, along with Life Science (Biotechnology), Information Technology, and Environment/Energy, all in an effort to revitalize the Japanese economy and maintain a competitive edge. Since then, government funding for nanotechnology has shown steady increases. Currently, there are three major public research organizations in the country:

- The Ministry of Education, Culture, Sports, Science and Technology (MEXT): Supports Universities and National Laboratories, including the National Institute of Materials Science (NIMS), the Institute of Physical and Chemical Research (RIKEN), and Japan Atomic Energy Research Institute (JAERI).
- The Ministry of Economy, Trade and Industries (METI): Supports the New Energy and Industrial Technology Development Organization (NEDO) and the National Laboratory: National Institute of Advanced Industrial Science and Technology (AIST).
- Other Ministries (combined as a third public research group): The Ministry of Public Management, Home Affairs, Post and Telecommunication (MPHPT), which supports the Communications Research Laboratory; and the Ministry of Agriculture, Forestry and Fishery (MAFF).

MEXT, along with the Japan Society for the Promotion of Science (JSPS) and the Japan Science and Technology Corporation (JST) provide the largest portion of nanotechnology funding; METI along with NEDO, is the next largest, followed by MPHPT and MAFF.

METI announced a nanotechnology commercialization execution plan in mid February 2003. METI’s New Industry Development Strategy (NIDS) for Nanotechnology and Materials expects to create five new nano-related industries

- Network and Nanodevice
- Nanobiotechnology
- Nano Environment and Energy
- Innovative Materials
- Nanometrology and Manufacturing

Japan clearly remains the leader in Asia in nanotechnology development. Its budget increase in 2003 catapults it ahead of the U.S. National Nanotechnology Initiative. This position will doubtless lead to an accelerated rate of nanotechnology advances.

**Foresight activities**

In 1970 the Council for Science and Technology began publishing technology projections by utilizing the so-called Delphi Method of repeated questionnaires. Since 1970, these technology foresights have been conducted and published approximately once every five years, for a total of seven times. In the Seventh Technology Foresight Report[24] nanotechnology is classified within the cluster „materials and processes“ under the heading „precision synthesis, structural control and development of new functionalities by manipulaton of atoms and molecules“ and has been evaluated as high priority topic. But also other forecasted technology trends of the seventh japanese delphi studies can be related to field of nanotechnology. In table I (see annex) there is a listing of the 20 topics rated most important from a japanese point of view for the following socioeconomical fields:

- Materials and Processing
- Information and Communication
- Electronics
- Life Sciences
- Medicine
- Agriculture and Food
- Resources and Energy
- Manufacturing
- Transportation
- Environment

In addition, the table gives an indication of the relevance of nanotechnology for the respective topic, based on own estimations.

## 3.3 Europe

On the European Union level in the 5th framework programme nanotechnological research projects were funded in different programmes (IST, GROWTH, QoL, etc.) with approx. 50 million € in the year 2001. In the 6th frame work programme nanotechnology funding will rise to annually at least 150 million €, whereby the emphasis will lie in the priority 3 ("nanotechnologies and nanosciences, knowledge based multifunctional material, new production processes and devices") and further in the priorities 1 and 2 ("genomics and biotechnology for health“ and „information society technologies")[25]. Beside the nanotechnology funding on European level, in many European countries, (e. g. Germany, France, United Kingdom, the Netherlands, Spain, Sweden and Switzerland) special research programmes in the field of nanotechnology have been established.

**Foresight activities:**

In Europe, Foresight activities emerged first at the national level., for example in Germany, France, the UK and the Netherlands have been undertaking a range of ‘futures research’ activities since the early 1990s.[26] At the European level, meanwhile there are several organizations supporting Foresight activities, e.g. The European Parliament and The European Parliamentary Technology Assessment Network, the European Commission (IPTS/JRC, DG Research), the European Foundation for the improvement of Living and Working conditions, the European Science Foundation etc. Several foresight reports have been published dealing with nanotechnology[27,28]. Since

2003 a nanotechnology network in europe has been established (www.nanoforum.org), which also is active in the field of foresight and publishes reports in this field.[29,30]

### 3.3.1 Germany

Nanotechnology activities in Germany started in the 1990s with a series of events and studies (Market and Delphi studies) focussing on nanotechnological subjects followed by first research projects in special areas (scanning probe technologies, lithography and x-ray technology). In 1998 the BMBF established and funded six nanotechnology competence centers (CC) and started with joint research projects for the first time, a multi departmental funding in the field of nanotechnology. A special focus was directed on nanostructured materials and bionanotechnology. The Federal Government recognises the importance of nanotechnologies as key enabling technologies for a wide range of technological sectors, including electronics, optical sciences and engineering, manufacturing, chemistry, materials, biotechnology and analytics. It has therefore made nanotechnology a key research policy priority and supports the exploitation of its commercial and job creating potential and a wider dialogue on the opportunities and risks. The key elements of the Federal Government's strategy for nanotechnology include:[31]

- Strengthening the scientific and technological basis of nanotechnology and promoting strategic research with regard to the use of nanotechnologies in a range of areas, such as materials science, information technology or optical engineering.
- Establishing networks involving the best public-sector research facilities, universities and commercial companies and continued support for Germany's six virtual nanotechnology competence clusters.
- Exploring and supporting potential applications of nanotechnologies by means of specific "beacon" projects that highlight the potential uses and benefits of nanotechnologies.
- Facilitating and promoting the establishment of new companies in high technology areas, including nanotechnology by means of existing programmes (e.g. EXIST spinout initiative, BioChance biotech start-up programme)
- Strengthening the role of SMEs. At present some 130 SMEs are involved in Germany's six virtual nanotechnology clusters: Measures will include training and qualification issues, initiatives to enable SMEs to gain better access to nanotechnologies and their potential uses, and a revision of the current funding guidelines for SMEs.
- Exploiting the opportunities of European and international collaborations within the framework of EUREKA, COST, the OECD and bilateral collaborations, but particularly within FP6.
- Promoting young scientists and interdisciplinary study and research
- Identifying qualification requirements at a very early stage and promoting the development of the necessary skills to exploit the commercial potential of nanotechnology.

- Initiating a wide debate on the opportunities, perspectives and risks of nanotechnologies, their potential uses and their implications for society.
- Exploring the need for a legal framework

**Foresight activities**

In Germany three Delphi reports on technology foresight were published, last one in 1998. To overcome the shortcomings of the delphi method in 2001 the Futur process has been established starting with a discourse session at which approx. 400 experts collected ideas questions concerning future social challenges. Futur relies on past experience and tested concepts – and applies new methods at the same time. Different methodical elements supplement each other:

- **Systematic nomination of actors**: the current Futur Circle of Participants is to be further developed. To this end, all actors are being asked to nominate other experts who would like to participate in the German research dialogue. Specific research for further specialists for individual topics or Focus groups will take place following this nomination round.
- **Focus groups**: Within the Futur process, small groups develop the topics. Interdisciplinary focus groups with not more than 30 participants analyse the key questions and the concrete need of research concerning their topics. They also formulate the possible contributions that their own disciplines might offer for the future development of the relevant area.
- **Workspace**: In between "real" meetings the research dialogue can continue on the virtual
  Futur platform on the Internet. Specific user groups have access to reserved rooms in the workspace. They can leave documents there and participate in discussions or online events such as Internet workshops.
- **Future dialogues**: Futur is intended as a social dialogue process. Futur wants to involve the public using the future dialogues and, using debates in different social groups, to stimulate more thinking about the future. The future dialogue topics come from Futur. At the same time the results of the talks serve as input for the German research dialogue: on the one hand they make a contribution to shaping the policy in the German Federal Ministry of Education and Research (BMBF) and on the other they give important stimuli for the development of lead visions.
- **Creative workshops**: Futur works with various types of workshops in order to stimulate "thinking about the future" and the development of future visions. This includes, for example, the Future workshops that are used in the generation of topics and within the framework of the future dialogue. Here, the Futur participants develop pictures of a desirable future and look for possibilities to realise these visions.
- **Scenarios**: Futur uses scenario techniques that have been developed for future research and the evaluation of the consequences of technological developments in order to depict the future in a vivid manner. The technique uses scenario workshops and scenario writing. In the workshops focus group participants together with the

Futur consortium develop sketches of future everyday life. These sketches should show a possible, but also a desirable future. Scenario writing attempts to yield a lively description of these sketches, understandable even to non-experts.

- **Surveys**: Numerous surveys among the participants of the Futur process produce a comprehensive feedback. In this way, a multistep decision process preceded the adoption of the first four lead visions: the actors chose their favourites via workspace. At the same time, the Innovation Council of the BMBF discussed the list of focus topics. In addition, the departments of the BMBF and the project managing agencies commented and evaluated the Futur focuses. Only after it had taken all different evaluations into consideration did the ministry make the final decision. Surveys will also play a central role in the forthcoming process. An online voting system is planned for the autumn: following the Futur conferences the Futur participants can then vote on topic priorities.
- **Systematic research for people and topics**: Futur undertakes systematic research in order to recognise future trends promptly, continually expand the Futur topic pool and to identify new experts for the Actors Group. To this end, Foresight activities in Germany and abroad are observed, research and support programmes closely followed and the position of various social groups examined and evaluated.

The subjects of the first lead visions are:

- **Understanding Thought Processes**

Understanding the way the human brain works and using this knowledge for information technology, medicine and learning research.

- **Creating Open Access to Tomorrow’s World of Learning**

In tomorrow's world of learning, further education throughout life is open to everybody.

- **Healthy and vital throughout Life by Prevention**

To ensure the quality of life for all social groups throughout life by comprehensive preventive health care.

- **Living in a Networked World: Individual and Secure**

People should be able to live in a networked world as they want, in security and with self-determination.

These lead visions are now implemented in BMBF research support programmes. This concerns also funding programmes within the range of nanotechnology. Nanotechnology will have a big impact as a key technology within the above mentioned lead visions in particular in the following areas:

- nanoelectronics for improved communication and information technnologies
- nanobiotechnology for improved health care
- converging technologies for improving human performance
- advanced human-machine interaction

Some of the lead innovations proposed within the framework programme for nanotechnology[32] announced in March 2004 can directly be linked to the Futur lead visions. For example the lead innovation „NanoforLife“ which will be implemented in

2005, aims at improving health care systems by applying nanotechnology developments in particular within the range of nanomaterials and nanobiotechnology.

### 3.3.2 France

In France the conception of nanotechnology is based on a strong link to the micro world and/or micro system engineering, which is regarded as a direct predecessor of nanotechnology. France has a strong commitment to nanosciences and nanotechnologies, but no structured research programme comparable with the German model. However some funding is allocated to the 'nanotechnology' field mainly from the Research Ministry through the 'Micro and nanotechnologies' National Research Network. National Research Networks were set up in 1999 to promote improved organisation of public research in France, with more links to industrial needs (industrial companies are participants of networks), better interaction among the different funding sources (mainly the Ministries of Research, Industry, Environment, Health, and some agencies like ADEME for Energy, ANVAR for innovation), and a bottom-up approach. An overall amount of funding is defined yearly by the government for each thematic network, and then shared by the different ministries and agencies, for each project selected. A project is a joint collaboration between public research organisations and private companies, on the basis of a 50/50 funding. The selection process is assumed by a steering committee for each network, giving priority to industrial needs, possible applications and potential impact on French competitiveness.

Some other initiatives are also being promoted: the CNRS has set up internal programmes (open to collaboration between CNRS research labs): 'Individual nanoobjects', 'nanostructured materials'. In Grenoble the CEA/LETI has promoted the creation of a big centre dedicated to the development of micro and nanotechnologies. This project is called MINATEC and represents an initial investment of about 120 M€, of which 50 M€ for new buildings which will be built close to the LETI clean rooms. In 2004 this centre will concentrate education and research skills, as well as incubators and networking activities at the same location. The LETI has already set up 'PLATO' the advanced platform for advanced microelectronics (sub 0,1 µm) and many projects in nanoelectronics in cooperation with the company ST Microelectronics. As a result Grenoble in the future should be the major research center in France, maybe in Europe, as regards nanotechnologies for optronics, electronics, and magnetics applications.

**Foresight Activities**

In France, programmes and planning are conducted to a relatively large extent by the government, i.e. by the Ministry of Industry (Ministère de l'Economie, des Finances et de l'Industrie) and the Ministry of Higher Education and Research (Ministère de l'Enseignement Supérieur et de la Recherche, MESR). Research is also done by industry. Public foresight activities experienced a revival in the 1990s:

- the first French Delphi survey on science and technology, a repetition of the 5th Japanese Delphi under the responsibility of the MESR, was launched in 1993; the study was not widely circulated.

- the Ministry of Industry developed another type of foresight: studies with relatively short-term perspectives that can already be considered as specific statements of position in the national context
- in 1993-1994 a study of the critical 100 key technologies for French industry (Les 100 Technologies clés) was launched and the report published in 1995; five years later, in 1998-1999 a second study updated the report with progresses in some important aspects (Technologies clés 2005). The report was published in October 2000.

The time horizon was a maximum of 10 to 15 years with the aim of identifying technologies worth support in around 2005. The study aimed at crossing the autonomous dynamics of science and the technology needs expressed by the market.

The thematic sub-groups were:

- Life Science, Health, Food
- ICT
- Energy – Environment
- Materials – Chemicals
- Building - Housing – Construction
- Transportation – Aeronautics
- Consumer Goods and Services
- Technologies and Methods for Design, Manufacturing and Management

Some of the identified key technologies of the thematic sub-groups can be assigned to or at least have some overlap to range of nanotechnology.

### 3.3.3 United Kingdom

In 1986 the National Initiative on Nanotechnology (NION) was initiated by the Department of Trade and Industry (DTI). was thus one of if not the earliest co-ordinated approaches towards nanotechnology in Europe. The goal of the NION was to give an early awareness of nanotechnology. A Nanotechnology Strategy Committee (NSC) was established to advise the government on all aspects of nanotechnology. Among the successes of the NION was establishing three centres of technology transfer. The NION recommended the establishment of a directed funding stream which gave rise to the LINK Nanotechnology Programme (LNP) which ran from 1988 to 1994. In this programme, the first project started in 1989 and was completed in 1991. The final round of funding was for 1994-1995, whereas the project ran until 1999. Meanwhile, different funding programmes exist, e.g. in the context of Interdisciplinary Research Collaborations (IRC) in Nanotechnology and University Innovation Centres (UIC).

**Foresight Activities**

In 1990 a vision document was prepared and highlighted specific areas within nanotechnology on which the UK should direct its focus and where there was felt to be sufficient expertise for the UK to be successful. The LNP can be considered highly successful with respect to funding projects, that otherwise would not have fitted in existing funding schemes, that increased commercial benefits and that helped UK to be more competitive. In the course of the LNP 14 centres of excellence were started which are still going strong. The UK technology foresight programme (1995-1998) was set up to establish research priorities. Nanotechnology was not explicitly mentioned at all. All foresight panels were criticised later on because of this. The absence of nanotechnology on the list of research priorities resulted in the loss of a co-ordinated national nanotechnology programme once LNP ran out.

Within the second UK foresight initiative (1998-2001) only the materials panel identified nanotechnology as an enabling technology. An interest on a broader range only re-emerged following the announcement of the large US nanotechnology initiative. Only recently did several research councils express an interest in nanotechnology for their respective fields and issued a call for an interdisciplinary research collaboration in nanotechnology.

### 3.3.4 Finland

Finnish nanotechnology programme started in the beginning of 1997 in co-operation with two funding organisations, Tekes and Academy of Finland. Some of the driving forces were the need to close the gap between so-called basic and, respectively, applied research in this area, the intellectual challenge of this rapidly evolving multidisciplinary branch of science, as well as the possibly tremendous economic impact nanotechnology may well have sometime in the future.

From the very beginning, the definition of what is nano was kept very wide. Actually, more important was that research concepts were new, fresh and potentially useful for future industries. From this point of view even projects with only one dimension in nano (such as MBE and CVD processes) were acceptable, and this dimension could be anything from 1 to 1000 nanometers. Other selection criteria were:

- high scientific / technological level
- vision of identifiable industrial potential;
- international and national cooperation
- tangible results.

Finally, 14 projects were selected for the programme and in contrast to most other Tekes programmes, no industrial funding was mandatory for the projects. Other operating principles were to keep bureaucracy and overhead cost at a minimum as well as to promote internal cooperation, but not to force it. It was initially quite obvious that very few projects would yield tangible commercial results during or immediately after the programme. However, some companies showed considerable interest and gave advice throughout the entire programme.

Though the programme was very small – somewhat 10M Euro – the results achieved so far are overall of high quality and scientifically significant. Some of the results have been commercialised but, as in other countries, the centre of gravity in this sector is located somewhere in the not-so-near future. The role of public funding is clearly emphasised for an embryonic technology such as nanotechnology. It would be disastrous for most companies to invest heavily in something where no revenue timetables can even be predicted.

The Tekes Nanotechnology programme ran for three years from 1997 to 1999. For the continuation it was decided to seek a closer relation with other existing disciplines as it has become clear that industry is more interested if the nano-approach is linked with another field like biotechnology or information technology. It can be said though that industrial applications are currently much closer than they have been before the start of the programme. Annual interdisciplinary seminars were held, which showed that substantial differences in the use of language existed and communication gaps needed to be overcome. While the programme began with weak links between the disciplines the experiences during the course of the programme proved to be a tremendous learning process and topics of common interest like nanoelectronics evolved.

Currently, nano activities are mainly carried out in the framework of other programmes for example „Miniaturizing Electronics -ELMO" (2002-2005) and „Clean Surfaces" (2002-2006). Tekes also funds the PINTA programme on "industrial utilisation of surface chemistry and physics". The total budget is €25 million.[33]

**Foresight activities**

As the main public R&D funding body in Finland, National Technology Agency Tekes actively monitors global technology trends in order to launch strategic activities to ensure the competitiveness of Finnish industries in medium and long term. Therefore, Technology Forecasting is one of the vital tools to tackle this challenge.

### 3.3.5 Others

Many other countries have their own national nanotechnology strategy and funding programmes. For example in Switzerland has strong nanotechnology activities for example the nanotechnology research initiative "TOP nano 21" (2000-2003), aiming at the efficient transfer of technological inventions into products ready for the market and promoting joint projects of universities and partners from industry.[34] Russia and Ukraine maintain research activities, especially on advanced materials synthesis and processing, and emerging programs have been announced in Eastern Europe.

## 3.4 Rest of the World

### 3.4.1 South Korea

Korea is committed to becoming one of the world's top ten countries for nanotechnology. This ambitious goal is supported by a 2001-2010 national nanotechnology program that is conducted under the auspices of the Ministry of Science and Technology (MOST). The projected budget of US$1.1B in 10 years is to come from MOST, several other agencies of the National Government, as well as the private industry. Korea's nanotechnology infrastructure is to be upgraded substantially. In addition to a National Nanofabrication Center at the Korea Advanced Institute of Science and Technology (KAIST) in Daejon, more than one specific-purpose Nanofabrication Center is to be built. Centers for Supporting Commercialization of nanotechnology, focused on nano-devices, nanomachining, or nanomaterials, are also to be built. The government portion of nanotechnology funding appears to be on track in Korea. Samsung and LG Electronics have also announced significant nanotechnology programs, and several small firms are now concentrating on nanotechnology.

**Foresight activities**

In Korea two Technology Foresight studies have been published in 1993 and 1998. In 2001 the national technology roadmap was established to comply with the need of a national strategy and economic growth toward 2012 and to follow top-down vision-driven approach to the identification of key technologies. In this process 5 main visions were proposed and 99 supporting key technologies were identified with nanotechnology as one of the most important one.

### 3.4.2 China

The five-year Chinese NNI was launched in 2001. The funds were envisioned to come from the Ministry of Science and Technology (MOST), which was to provide roughly half, as well as from the State Development and Planning Commission, the Ministry of Education (MOE), the Chinese Academy of Sciences (CAS), the Chinese Academy of Engineering, and the National Science Foundation of China. Exact figures for actual spending remain elusive, but results from that spending detailed below are clear:[35]

- For the ten-year period from 1991 to 2001, China ranked third in number of publications in nanotechnology, behind the U.S. and Japan, and ahead of Germany. From 1999 to 2001,
- Between 1985 and 2001, there were 956 nanotechnology patents granted in China. The number of patents in nanomaterials in China is about 9% of the total in the world, whereas Chinese patents in nanobiotechnology and nano electronics represent only 3% and 1%, respectively, of the total in the world.

The largest single entity created by China’s NNI will be a National Nano Science Center in Zhongguancun, Beijing. Governmental investment will be 250 million yuan (approximately US$30M). The Center will be supported by CAS, Peking University, and Tsinghua University, and will provide a technological platform for the nation's nanotechnology efforts. China remains a very attractive market for foreign capital investment and in the future China will likely become a major supplier of nanotechnology products, primarily materials.

### 3.4.3 Israel

Nanoscience and Nanotechnology (NST) was one of the emerging fields that caught the interest of the Israeli scientific community in the late nineties.

A strategic research programme was launched by the Ministry of Science in which NST topics were selected as areas of national priorities, and some industrial R&D efforts:

- The National Committee for R&D of Advanced Materials and Chemical Technologies selected Nanomaterials & Nano-chemistry as one of 5 topics of national priority for strategic research. Main Goals were: Develop advanced methods for fabrication of nanocrystals, self-assembling supra-molecular systems, nanoscale control of properties,…
- The National Committee for Microelectronics & Electrooptics Technologies selected Nanotechnology as one of national priorities. Main research areas are: Electronic/optoelectronic nanodevices, NEMS, Inertial Systems, Microlenses, Integration of quantum dots with microdevices, nanotubes, nanostructures,etc.

**Foresight Activities**

In Israel foresight activities on nanotechnology started with an extensive study commissioned by the Israeli government in order to evaluate the field of nanotechnology, its development trends and the potential applications. The study was executed by ICTAF. The study aimed at presenting the state of the art, development trends, mapping of activities in Israel and potential applications. It focused on the following issues:

- Nanostructures and quantum devices, Nanoelectronics
- Nanochemistry, Nanomaterials
- Nanorobotics and Molecular Robotics
- Future application areas and anticipated products

Through the study the nanotechnology was identified as an important emerging technology, whereby most activities were focused on nanoscience and a high potential for future applications. In 1999 a second ICTAF study on Nanotechnology was executed using a Delphi-type survey. Several significant realisation steps have followed it. As far as the funding is concerned the situation in Israel is very special in that the budget of the Ministry of Science is comparatively small and that substantial parts of the research funding are raised abroad due to initiatives of the universities themselves.

# 4 POLICY MEASURES

Governments all over the world have realized the potential of nanotechnology as a key technology for innovation and economic prosperity in the 21st century. Nanotechnology is growing in an environment where international interactions accelerate in science, education, and industrial R&D. A global strategy of mutual interest is envisioned by connecting the programs of contributing countries, professional communities, and international organizations. Although a conformation of funding policies in the field of nanotechnology on international level has taken place to some extent there are still some different approaches and strategies, which can be identified:

- Leading economic nations like the United States, Japan and Germany have established research programmes covering the whole range of nanotechnology and nanoscience, while smaller countries usually have a focus on subtopics for example Korea with intensified efforts in the range of nanoelectronic memory chips or Australia, which has identified nanoscale photonics as a focus for government investment.
- Some countries like Japan, Korea, China or Switzerland have adopted coordinating offices at the national level similar to the U.S. National Science and Technology Council, while other countries like Germany or France have a more or less decentralized multitrack approach.

International activities and agreements have increased in importance. Examples are the agreements between the U.S. National Science Foundation and European Community (EU), Asia Pacific Economic Cooperation, Russia, and China, New York, and Quebec. For example, NSF and the European Community have organized periodical workshops (four workshops were held in 2002 on Manufacturing at the Nanoscale, Revolutionary Opportunities of Nanotechnology, and Societal Implications, Tools for Measurements and Manufacturing, and Materials) and sponsored a joint solicitation for proposals. Japan, Taiwan, and several other countries began to focus on the nanoscale as the most efficient manufacturing domain and the development of instrumentation and standards, and began establishing industrial partnerships. In addition, the education of future workers is a focus in the United States, the European Communities, Korea, and Canada.

## 4.1 Research and Development

With regard to research and development activities the following thematic areas can be regarded as the most important in the range of nanotechnology on international level:

- Nanostructured Materials
- Nanoelectronics
- Nanophotonics
- Nanobiotechnology
- Nanoanalytics

Although some differences between national R&D strategies on nanotechnology exist, there are some key points, which are regarded important in most of the countries:

- Establishing networks and partnerships involving public-sector research facilities, universities and commercial companies
- Establishing top-class research centers as incubators for innovation and technological advancement
- Development of instrumentation and standards
- Promoting interdisciplinary study and research
- Fostering international cooperation

## 4.2 Innovation Policy

Future R&D results will fundamentally change the way materials and devices are produced. This will mean lighter, stronger and programmable materials, with reductions in life-cycle costs through lower failure rates, and elements which are harmless to the environment and need less power for their running. If new products are to fulfill the needs and desires of customers and time their arrival on the market correctly, a new approach is required to the management of nanotechnology innovation:[36]

- Interdisciplinary approaches imply a different R&D strategy and a new mode of science management in companies, institutes, universities and funding agencies.To prevent duplication of work, stronger coordination of research programmes across disciplines and European countries is necessary. R&D on nanotechnology is characterized by a huge amount of highly specialist knowledge, and crossfertilization offers the chance of revolutionary innovation. Europe has a high density of industry, many high-tech companies, enthusiastic researchers, and venture capital organizations which are willing to support new directions. An interdisciplinary approach would be assisted by creating networks, with research topics related to areas with a high market potential.

- Innovation research and development processes need to be distinguished. For the most part innovations cannot be foreseen, whereas in development processes cooperation can be organized into networks with clearly specified tasks. Some topics are related to basic questions (e.g. the development of materials with corrosion resistance), while others depend on demand from industry (e.g. future lithography techniques for integrated circuits) or society (e.g. environmental questions), leading to a research race to find the first solutions. Not all the applications that are developed find markets. In emerging fields such as nanotechnology, where new findings and innovations come up nearly every day, the need for flexible strategies is evident. While research and innovation mostly depend on the knowledge of individuals, industrial developments are mainly performed in networks. Both elements need financial and infrastructural support. Inventors need fast, practical help in realizing ideas with importance for the future, while companies need competent interdisciplinary networks to turn research results into products.
- Innovation management means defining time scales, costs and risks at an early stage in product commercialization. This needs to be organized horizontally (different branches and disciplines) as well as vertically (along the productivity chain: education – research – development – production – commercialization). Besides the scientific elements and the role of European and national funding agencies, it also implies early involvement by industrial innovation departments, venture capital representatives and regional decision-makers. There should be intensive communication between network partners, periodic interdisciplinary discussions and lectures, communal use of resources (computation centres, databases, expensive hardware), and a networked approach to detailed tasks. In this way, the network can become a virtual centre of competence that helps to generate and secure hi-tech jobs in Europe.
- Increasing calls can be observed for more public discussion about nanoscale science and technology. There have been complaints about a growing gap between rapidly rising investment in nanoscience and industry, and very limited study and debate about the social and ethical implications of new nanotechnologies. Ignoring the public can create the risk of criticism and major adverse impacts on reputation and business prospects later on. Controversies about nuclear technology, genmanipulated food or "mad cow disease" are examples of the loss of public trust in regulatory agencies dealing with complex scientific problems. Particularly in the United States participation methods will find increasing application in the future also in the field of nanotechnology as a consequence of a federal law passed in December 2003. Participation in nanotechnology in that meaning is not restricted to being informed or consulted about government action, but also includes ways in which researchers, engineers, and citizens in general may be empowered to take part in an open and responsible process of technological development.[37]

## 4.3 Education

Nanotechnology is a multidisciplinary field with scientists working in physics, chemistry, biology, engineering, information technology, metrology, and related fields beeing involved in nanotechnology research and product development. Identifying qualification requirements at a very early stage and promoting the development of the necessary skills to exploit the commercial potential of nanotechnology has been identified as an important aspect in many countries. Some countries with the United States in a leading position here have started activities to meet these challenges. However, until now only few approaches can be found to adapt university curricula concerning nanotechnology. Today, few universities offer degrees in nanotechnology, although a vast number of research universities offer courses in the field. Many universities also offer undergraduate experiences in interdisplinary centers (see www.nano.gov). Also in other countries like Germany, Switzerland or Denmark there are approaches for nanotechnology degrees and programmes. Although it is incontestable that education is a very important topic in the range of nanotechnology, there are some controversies which approach is best suited to guarantee well trained workers and students in the future. From the side of industry, it is often argued that a good nanotechnologist should have a very deep knowledge in his discipline but is also able to talk to people from other disciplines. While nanotechnology is an interdisciplinary and multidisciplinary field, there is a concern that students could pursue too broad an education and end up knowing a little about a lot of fields, but not enough in any one field to make significant contributions.

## 4.4 Societal and Environmental Aspects

Since a few years in the United States and some european countries it has been realized, that research on societal implications will be necessary to take advantage of nanotechnology sooner, better, and with greater confidence. Moreover, technically competent research on the interactions between nanotechnology and society will help mute speculative hype and dispel some of the unfounded fears that sometimes accompany dramatic advances in scientific understanding.

So far, the state of research into potential environmental and health impacts of the production and use of nanotechnological processes and products is unsatisfactory. Considerably greater research efforts are urgently needed here, as the lack of knowledge of the environmental and health consequences could create barriers to the market launch of nanotechnologies. From the current position the main potential impacts on the society and the environment can be summarized as follows:[38]

- Beneficial effects of nanotechnology for the environment can be expected from the conservation of material resources, the reduction in the volume of pollutant byproducts, increased efficiency in energy conversion, reduced energy consumption and the removal of pollutants from the environment.
- Potential hazards for human health and the environment may result from an uncontrolled release of nanoparticles and nanomaterials, which is often subject of publications and newspaper articles in recent times. Concern about possible negative

consequences of inhaling nanoparticles has so far been based primarily on analogies with the results of available studies on the effects of ultrafine particles. Also other incorporation routes into the human body are possible like skin penetration, ingestion or medical application of nanoparticle based drugs. The human organism is already brought into extensive contact with nanoparticles through food and cosmetics (e.g. dyes, UV filters). However, knowledge of the pharmacokinetics of active ingredients administrated with nanoparticles is still only in its infancy. We also have virtually no knowledge of how nanoparticles disperse and their impacts on the environment, and specifically long term consequences. Particularly noteworthy here are materials which do not occur in nature, like fullerenes or nanotubes, which constitute new materials.

- To date, little attention has been paid to nanotechnology in practical philosophy and ethics. In visions of nanotechnology, we repeatedly see aspects which dissolve the boundaries between what constitutes a human being, and what they can create with the help of technological achievements and applications. Such aspects relate e.g. to the penetration and modification of the human body by attempts to supplement or replace its biological components by nanotechnology components, and to network it with external machines or other bodies or body parts. The emerging convergence of various technologies are strengthening not only hopes of technological progress but also concerns about the consequences of this. The further development of nanotechnology should accordingly be accompanied by ongoing research on ethical and political questions relating to the changing relationship between humans and machines and nature and technology.
- Problems of distribution and equitable use of the fruits of technological progress are other likely societal consequences of the use of nanotechnology. Questions of the distribution of opportunities could become urgent in at least two ways – first, within technologically more developed societies, and second in relation to less developed societies. Concerns of a possible "nanodivide" between these two are based on the assumption that nanotechnology can contribute to both new and expanded options for individual self-determination (e.g. in the healthcare sector) and also considerable improvements in the competitiveness of economies. Political measures can promote equality of opportunity and sustainable global development. There are further political responsibilities in terms of avoiding damage, e.g. in terms of possible adverse implications for patient data protection of new medical diagnosis and monitoring possibilities.
- Another field in which considerable progress is expected as a result of nanotechnology is military applications. The further development of nanotechnology is accordingly likely to involve increased need for action in security policy. There is also (primarily, but not only, in the United States) considerable interest in military applications of nanotechnology. Although several of the possible security problems arising in scientific debate (e.g. from self-replicating nanobots) may seem less urgent, there will probably be growing calls for security and arms control policy measures in future as a result of further advances in nanotechnology military research and development.

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## Annex

**Table I: Top20 topics of the 7th japanese Delphi Report and assessment of nanotechnology relevance**

| Topic | Im-Ind* | Nano Rel.* | Time* |
|---|---|---|---|
| **Environment** | | | |
| Widespread use in virtually all types of automobiles of a technique capable of meeting an emission control standard that specifies a nitrogen oxide emission limit of 0,1 to 0,2 g/km | 90 | h | 2011 |
| Practical use of technology capable of reducing particulate matter emissions from diesel vehicles to 10% of current levels | 90 | h | 2011 |
| Large reduction of the amount of buried industrial waste as a result of advances in the reorganization and integration of industrial technology aimed at reducing waste emissions to zero | 89 | h | 2018 |
| Introduction of an environmental tax in Japan with the aim of preserving the global environment | 84 | l | 2009 |
| Reduction of global carbon dioxide emissions to 20% below the 1990 level | 84 | m | 2027 |
| Widespread use of products based on LCA (life cycle assessment) concepts that facilitate recycling and reuse | 82 | m | 2012 |
| Widespread use up to at least 20% throughout the world of low-polluting vehicles that do not cause air or noise pollution for urban transportation (electric vehicles) | 81 | h | 2018 |
| Elucidation of health disturbances caused by long-term exposure to low concentrations of endocrine-disrupting chemicals (so-called environmental hormones) | 77 | l | 2015 |
| Widespread use of technology for removing POPs (persistent organic pollutants) such as dioxin from soil and sediment | 75 | m | 2017 |
| Establishment of a technique to predict the fate of newly discovered chemical substances through the accumulation of knowledge on matters such as the behavior of persistent chemical substances in the environment | 73 | m | 2018 |
| Elucidation of the impact of marine pollutants on marine ecosystems on a global scale | 73 | l | 2018 |
| Widespread use of high-efficiency processes for treating refractory and hazardous materials using biotechnology-based waste water processing systems | 71 | h | 2015 |
| Widespread use of biodegradable plastics that can be fully decomposed by microorganisms, as material for containers and packaging with short service lives | 71 | m | 2014 |
| Widespread use of alternative substances or processes for the three gases SF6, HFC and PFC that were added to the list of gases subject to control in the Kyoto Protocol | 69 | l | 2012 |
| Large reduction of the number of allergy-sufferers as a result of elucidation of the relationship between environmental pollutants and allergies | 68 | m | 2019 |
| Practical use of effective technologies for restoring ocean areas contaminated by tanker accidents, technologies utilizing marine microorganisms | 68 | l | 2014 |
| Elucidation to a high degree of accuracy of the mechanism of generation, absorption and fixation of carbon dioxide | 67 | l | 2015 |

| | | | |
|---|---|---|---|
| Widespread use of methods for on-site detoxification of soil over limited areas contaminated with heavy metals or chemicals | 67 | m | 2015 |
| Development of a bio-monitoring system effective for almost all chemicals that are considered to be endocrine disrupters | 67 | m | 2018 |
| Widespread practice of global-scale monitoring of various factors causing air, water or other pollution | 66 | l | 2017 |
| **Transportation** | | | |
| Widespread use of technology to reduce the harmful components of exhaust gas from large trucks to 1/10 of present levels, such as diesel exhaust catalysts, particulate traps, lean-burn NOx catalysts and high precision combustion technology | 88 | h | 2011 |
| Widespread use of electric cars equipped with fuel cells | 83 | h | 2014 |
| Resolution of the waste problem of scrapped vehicles through advance in motor vehicle recycling technology | 82 | m | 2015 |
| Reduction by half of the traffic accident fatality rate through the use of anti-collision systems that apply ITS technology | 79 | m | 2015 |
| Development of a system that detects the initial mild tremors of a plateboundary earthquake at appropriate locations, and safely stops trains as necessary to avoid places that have a high risk of collapse (in response to the expected earthquake) | 75 | l | 2014 |
| Widespread use of an urban road traffic control system that can ascertain traffic volume for each direction and make necessary adjustments to achieve optimum traffic flow so as to save energy and improve the environment | 73 | m | 2012 |
| Development of public transport facilities and an environment in which elderly people and disabled people can readily move around within their sphere of life with ease and safety | 71 | m | 2015 |
| Practical use of safe and simple FRP vessel disposal technology via pulverization, incineration, chemical treatment, etc | 71 | l | 2013 |
| Reduction of the noise generated by heavy-duty freight trucks to the passenger car levels through improvements in engines, transmissions, mufflers, tires, road surfaces, etc | 67 | l | 2014 |
| Utilization of new materials in rails and wheels and improvements in the technology of structure and vehicle construction | 66 | h | 2014 |
| Practical use of a system in which the radical automation of air traffic control through advances in computer technology results in a labor saving of about half the current level | 65 | h | 2014 |
| Promotion of the use of different means of transport, such as the parkand- ride system, using real-time information on public transport and road traffic | 65 | l | 2011 |
| Widespread use of a system that facilitates the efficient and automatic check and maintenance of railway vehicles, structures, tracks, through the use of robotics technology to cope with labor shortages and improve safety | 64 | m | 2012 |
| Practical use of floating of -shore airports with 3,000m-class runways with a service life of about 60 years | 63 | l | 2013 |
| Widespread use of permeable road pavement, leading to improvements in the urban environment in ways such as the recharging of ground water and alleviation of the “heat island" phenomenon | 63 | l | 2011 |
| Establishment of quantitative ship safety evaluation methods using past accident data or disaster simulation to set ship safety standards | 60 | l | 2012 |
| Practical use of a shipbuilding system centering on a large-scale product database in which intelligent design production modules are dispersed over a network, leading to a reduction in shipbuilding labor requirements to about half the present level | 60 | l | 2013 |
| Practical use of a marine traffic control system that facilitates the safe and efficient movement of all ships, including fishing boats and pleasure craft, in congested areas such as Tokyo Bay | 60 | l | 2013 |
| Practical use of train-mounted energy equipment such as flywheels and fuel cells to accumulate regenerative energy and reduce the load on transformer substation at peak time | 59 | h | 2014 |
| Practical use of maintenance technology that enables safe management extending over the life cycle of the ship, such as measuring plate thickness, and detecting and estimating the progress of cracks | 59 | l | 2012 |
| **Manufacturing** | | | |

| | | | |
|---|---|---|---|
| Widespread use of a design-manufacturing-collection-recycling system in which manufacturers are obligated by law to collect and dispose of disused products, and at least 90% of used material is recycled | 90 | l | 2015 |
| Widespread use of low entropy-generating eco-factories, which give due consideration to the impact on local ecosystems throughout product life cycles, from manufacture to disposal | 87 | m | 2017 |
| Widespread use of a production destruction manufacturing system in which a production system of design - production - use - disuse is combined with a resources recycling system of collection - dismantling and sorting - reuse - production | 87 | m | 2017 |
| Widespread use of zero emission factories as a result of advances in the development of carbon dioxide collection technology | 86 | m | 2021 |
| Development of semiconductor microprocessing and measuring technology of 1nm resolution for manufacturing 0,01 micron-rule LSI | 84 | h | 2013 |
| Widespread use of non-fossil energy sources (wind, geothermal, PV/solar heat, and waste heat) in all areas of manufacturing | 83 | h | 2018 |
| Practical use of processes capable of customizing material through material manufacture control technology at molecular and atomic levels | 81 | h | 2017 |
| Practical use of mounting technology at the several μm level capable of realizing ultra-small wearable devices that integrate optoelectronics, microelectronics, and micromachines | 80 | h | 2014 |
| Widespread use of cogeneration systems (fuel cells and micro-gas turbines) in the manufacturing industry | 80 | m | 2013 |
| Practical use of technology for optimizing energy usage in the manufacturing processes through the storage of large amounts of electricity (superconductors, flywheels, and condensers) | 79 | m | 2019 |
| Practical use of technologies for mass-producing hydrogen by decomposing organic substances through application of solar energy and biological systems | 79 | m | 2020 |
| The relationship between universities and companies becomes much closer through such measures as expansion of internships in the science and engineering field, greater interchanges between industry and academia, and expansion of corporate cooperation in research and education, and through this, universities in Japan come to play a greater role in technological innovation in manufacturing | 78 | l | 2012 |
| Establishment of a common global language (including software) that can express manufacturing-related information and knowledge, leading to development of interface technology capable of accurately communicating information, including intentions, through a human-machine-information system, regardless of differences in language and culture | 78 | m | 2017 |
| Widespread use of a local (remote areas) manufacturing system without a trial production process that produces image prototypes with 3-D digital models, and transmits digital data to the manufacturing plants | 76 | m | 2009 |
| Advances in digitalization and increased sophistication of industrial robots give rise to radical changes in job opportunities and job forms for workers in the manufacturing industry | 75 | m | 2012 |
| Practical use of angstrom-order ultra-precision processing technologies (machining, analysis, testing and in-situ monitoring) as a result of advancements in beam technology (ions, electrons and lasers), control technology, and sensor technology | 75 | h | 2012 |
| Widespread use of manufacturing systems where elderly or disabled people can work without difficulty | 73 | l | 2014 |
| Widespread use of manufacturing technology for controlling specified characteristics so that subsequent testing is unnecessary through in-situ monitoring of chemical reactions and feedback to the control system in highly complex and precise manufacturing processes, such as LSI manufacturing | 73 | h | 2014 |
| Widespread use of technology that assesses potential risk at an industrial estate, company or manufacturing facility by assuming a multiple chain accident, and estimating the damage caused, including the impact on the surrounding area | 73 | l | 2016 |
| Widespread use of virtual manufacturing systems that support manufacturing activities such as design, development, production, operation, maintenance and waste disposal | 72 | m | 2011 |
| **Resources and Energy** | | | |

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| Practical use of rational methods of collecting and recycling useful substances in urban garbage based on an LCA (life cycle assessment) perspective | 83 | l | 2014 |
| Practical use of economical techniques to recover deep ocean metal resources, such as manganese nodules, colloidal or hydrothermal deposits of heavy metals, and cobalt-rich crusts | 65 | l | 2022 |
| Practical use of iron making process whose fuel consumption is less than half the current level, through the use of hydrogen or methane | 63 | l | 2018 |
| Development of technology for manufacturing ultra-thin metal foil less than 1 micron in thickness | 60 | m | 2012 |
| Widespread use of recycled alkali metals or alkaline earth metals in Japan | 58 | l | 2017 |
| Partial replacement of copper and aluminum by organic electrical conductors such as polymers | 57 | h | 2015 |
| Development of semiquantitative evaluation technology for mineral resources based on data taken by artificial satellites | 57 | m | 2016 |
| Practical use of new functional materials such as high-strength copper developed through microstructural control | 56 | h | 2015 |
| Practical use of ultra-deep drilling and excavating technologies applicable to severe condition of up to 400m and a depth of 15 km | 52 | m | 2019 |
| Widespread use of hydrometallurgical process with a copper and noble metals extraction rate equivalent to the ore dressing-dry refining process | 50 | l | 2015 |
| Establishment of accurate rainfall forecasting technology capable of providing timely flooding and landslide forecasts | 80 | l | 2013 |
| Widespread use of technology for removing a wide range of pollutants such as endocrine-disrupting substances in addition to common pollutants such as phosphorus and nitrogen compounds in sewerage and other wastewater treatment | 79 | m | 2016 |
| Widespread practical use of water treatment technologies that contribute to improvement in the environmental quality of rivers and lakes and facilitate the use of water taken from them over a wide area | 77 | h | 2013 |
| Obtainment of insight into the mechanism by which climate change causes unusual precipitation (heavy rain or draught), and widespread introduction of measures to ensure adequate water resources in response to changes in precipitation characteristics | 75 | l | 2017 |
| Development of a highly accurate environmental impact prediction technology for trace water contaminants that are carcinogenic or endocrine-disrupting,etc | 73 | m | 2015 |
| Widespread use of water supply pipes made of new materials that are highly resistant to earthquakes and other disasters and their installation technologies | 68 | m | 2013 |
| Widespread use of technology for efficiently removing soil deposit in reservoirs by flushing appropriate amounts of storage to prevent its buildup so as to rejuvenate the dams and extend their service life | 66 | l | 2014 |
| Widespread use of levees designed not to break even if overflow occurs and constructed by using high-standard levees and new materials | 64 | l | 2014 |
| Widespread use of treated recycled water at housing complex, small-scale industries, etc following advances in sewage and wastewater treatment technologies | 61 | m | 2013 |
| Widespread implementation of conservation and rational use of groundwater following advances in technology for monitoring groundwater flow, level and distribution | 60 | l | 2017 |
| **Agriculture and Food** | | | |
| Determination of the whole DNA sequence of crops (e.g rice) to isolate useful genes | 89 | h | 2008 |
| Practical use of rational resources management technology once elucidation of the reproduction processes of major fishery resources makes it possible to predict long-term (10-20 years) changes | 88 | l | 2024 |
| Elucidation of the mechanism by which the toxicity of endocrinedisrupting chemicals is manifest and its effect on reproductive functions, behavior, brain functions, immune functions and the establishment of safe limits for humans and livestock | 87 | m | 2015 |
| Examination of the safety of genetically modified farm products from both food and environmental perspectives, and development of an evaluation method that can gain the understanding of consumers | 87 | m | 2011 |
| Integration of food safety administration, and establishment of forums for extensive discussions on food safety and effective use of feedback for administration | 86 | l | 2009 |

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| Development of factories that purify river water by fixing bacteria that breakdown dioxin and other endocrine disrupters in carriers such as porous charcoal | 86 | l | 2015 |
| Practical use of technological structures and systems for the proper use of forests while preserving the forests and their functions (maintenance of biodiversity, environmental purification, and provision of scenery and comfort) | 86 | l | 2017 |
| Development of food capable of supporting a healthy aging society from a nutritional perspective by preventing a decline in anti-oxidation, brain and chewing functions | 84 | m | 2012 |
| Widespread use of environmental repair technology capable of cleaning the pollution of closed water areas, such as Kasumigaura, to prewar levels using organism and ecosystem functions | 83 | m | 2018 |
| Reduction by half of the amount of agricultural chemicals by using predominantly biological methods of crop protection (use of natural enemy organisms, pheromones and allelochemicals) | 82 | l | 2015 |
| Widespread use of agriculture, forestry and fisheries material and containers, such as multi-film for open-field farming and fishing gear, made from biodegradable material | 82 | l | 2011 |
| Widespread use of local weather monitoring systems, and technological systems for reducing crop damage from cold weather, floods, drought, wind and the like | 79 | l | 2015 |
| Widespread use of biomass energy technology using farm products and by-products | 79 | l | 2014 |
| Practical use of technology for preventing crop replant failure through biological methods, such as controlling microflora in the soil | 78 | l | 2016 |
| Development of technology for the efficient production of beneficial substances such as medicines using cultured animal cells | 74 | m | 2011 |
| Development of technology capable of accurately estimating high-order structures from primary protein structures of protein, and freely designing 3-D structures with physiologically active functions | 73 | h | 2016 |
| Widespread use of technology for dissolving and facilitating crop uptake of unavailable phosphorus fixed in the soil through the use of microorganisms | 73 | l | 2014 |
| Practical use of global monitoring systems that constantly monitor changes in agriculture, forestry and fisheries resources and environment through advances in high-resolution remote sensing technologies | 72 | l | 2013 |
| Widespread use of eco-power generation systems using biogas generated from livestock waste and food waste as fuel cells | 71 | m | 2015 |
| Widespread use of functional foods capable of preventing lifestyle diseases according to individual body characteristics | 71 | h | 2015 |
| **Medicine** | | | |
| Elucidation of carcinogenic mutation mechanisms | 89 | h | 2014 |
| Elucidation of cancer metastasis mechanisms | 87 | h | 2014 |
| Elucidation of the arteriosclerosis contraction mechanisms | 84 | h | 2013 |
| Elucidation of the contracting mechanisms in Alzheimer’s disease | 82 | h | 2014 |
| Widespread use of methods to prevent cancer based on genetic diagnosis | 81 | h | 2017 |
| Widespread use of early diagnosis methods based on blood tests for almost all cancers | 79 | h | 2016 |
| Widespread use of scientific guidelines for lifestyles (nutrition, rest and exercise) to prevent lifestyle-related diseases | 78 | l | 2010 |
| Improvement in the average five-year survival rate for all types of cancer to more than 70% | 78 | m | 2020 |
| Elucidation of individual aging mechanisms | 75 | m | 2021 |
| Widespread use of palliative care in the final stage of life of elderly people | 72 | l | 2010 |
| Widespread use of regenerative treatment technology for damaged organs using embryonic stem cells | 71 | l | 2020 |
| Practical use of effective methods against cancer metastasis | 71 | h | 2017 |
| Widespread use of treatment methods capable of completely curing Alzheimer’s disease | 70 | h | 2020 |
| Early elucidation of the appearance of unknown virulent pathogens through a global surveillance system to prevent their world-wide spread | 70 | m | 2017 |
| Widespread use of a system in which all medical data of an individual, such as test results, medical history, and prescribed medications, are stored on a single card | 69 | m | 2011 |
| Widespread use of drugs to cure viral liver disease | 68 | m | 2014 |
| Widespread use of non-invasive diagnosing methods to determine the level and extent of arteriosclerosis | 66 | h | 2012 |

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| Development of treatment methods capable of completely curing allergies such as atopic dermatitis | 66 | m | 2016 |
| Widespread use of an oral insulin treatment method | 66 | h | 2014 |
| Development of a cell therapy method for myocardial infarction | 66 | m | 2015 |
| **Life Sciences** | | | |
| Identification and classification by the molecular etiology of the genes related to diabetes, hypertension, and arteriosclerosis, which are typical lifestyle diseases that exhibit multiple-factor hereditary traits | 93 | m | 2013 |
| Development of methods for surmising new functions of proteins from DNA base sequence data | 93 | h | 2009 |
| Practical use of effective means to prevent metastasis of cancer | 93 | h | 2017 |
| Widespread use of drugs capable of preventing the occurrence of certain types of cancer | 91 | h | 2016 |
| Widespread use of medical treatment that leads dysdifferentiating carcinogenic cells into normal state by controlling the signal transduction in carcinogenesis of cells | 91 | m | 2020 |
| Development of technologies which dramatically improve photosynthetic functions in order to increase food production and preserve the environment | 90 | h | 2018 |
| It becomes possible to determine the entire base sequences of an individual including genetic structure and SNP (single nucleotide polymorphism) promptly and cheaply, leading to widespread use of such methods for diagnosis and tailor-made treatment | 90 | h | 2012 |
| Practical use of a effective drug against multiple-drug-resistant bacteria, including vancomycin-resistant bacteria | 90 | l | 2011 |
| Complete understanding of the factors contributing to stem cell proliferation, and widespread use of the practice of proliferating stem cells, as necessary, in vitro and using them for medical treatment | 89 | m | 2018 |
| It becomes possible to differentiate separated stem cells into any organ in vitro, leading to clinical application of such techniques | 89 | m | 2019 |
| Development of technology to regenerate targeted organs from differentiated animal cells | 88 | m | 2017 |
| Elucidation of the environmental factors and regulatory mechanisms of immune response which triggers allergies such as hay fever and atopy, enabling complete control over immediate type hypersensitivity diseases | 88 | h | 2016 |
| Production of biodegradable plastics, such as bioplastics using microorganisms and plants, accounts for more than half of the total volume of worldwide plastic production | 88 | m | 2015 |
| Development of high-speed genome analysis technology, and determination of the entire genome sequences of at least 50 important animal and plant species | 88 | h | 2009 |
| It becomes possible to prevent the progress of Alzheimer’s disease | 87 | h | 2017 |
| Establishment of technologies for predicting bioactivity and functional domain of proteins from their higher-order structures | 87 | h | 2012 |
| Practical use of cancer treatment methods capable of distinguishing cancerous cells from normal cells, and targeting those cancerous cells | 87 | h | 2016 |
| Formation of consensus among the research community on guidelines on ethics-based research controls in the life science field in Japan | 85 | m | 2008 |
| Identification of most immunologically functional molecules responsible for organ transplant rejection, enabling organ transplantation free of side effects | 84 | h | 2017 |
| Guidelines for life science research in Japan’s research community form the basis for enactment of related laws and regulations, and are shared by the entire Japanese society | 84 | l | 2011 |
| **Electronics** | | | |
| Practical use of technology enabling the mass production of LSI with minimum pattern dimensions of 10nm | 91 | h | 2015 |
| Widespread use of a portable multimedia wireless terminal operating at about 100 Mbps which can be used throughout the world | 90 | h | 2013 |
| Practical use of non-volatile, rewritable random access semiconductor memories with more than 100 Gbits capacity | 88 | h | 2016 |
| Development of logic LSIs with 10 GOPS (giga-operations per second) performance and power consumption of 10 milliwatts or less | 86 | h | 2018 |
| Practical use of TOPS (tera-operations per second) level microprocessors | 86 | h | 2019 |
| Widespread use of 10 Gbps optical subscriber systems in homes | 86 | h | 2014 |

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| Practical use of technology that can completely automatically design high performance LSIs with several hundred kilo gates or more when given the required system-level specifications written in a high-level language such as C | 85 | h | 2011 |
| Practical use of VLSI with more than 256 Gbits of memory per chip | 85 | h | 2015 |
| Practical use of card-size wireless communication instruments capable of changing specifications, such as center frequencies, band width, modulation method, and error correction method, by software operations | 85 | m | 2012 |
| Practical use of LSIs operating at clocking frequencies of more than 50 GHz | 84 | h | 2015 |
| Practical use of optical communication systems capable of transmitting signals through multiplexed 1,000 channels at 100 Gbps over a single optical fiber | 84 | h | 2016 |
| Practical use of single atom/molecule manipulation techniques as methods for device fabrication and gene manipulation | 83 | h | 2015 |
| Practical use of 100M gate scale LSIs whose functions are reconfigured in real time | 81 | m | 2014 |
| Practical use of card-sized automatic interpretation system (voice input/output) | 81 | h | 2015 |
| Development of a magnetic recording hard disk capable of recording one terabit density per square inch | 79 | h | 2015 |
| Development of one-chip ubiquitous computer with which information can be exchanged anytime, anywhere, and with anyone | 79 | h | 2014 |
| Practical use of optical memory of one terabit or more per square inch | 77 | h | 2018 |
| Practical use of flat panel displays of at least A3 size with display quality equivalent to high-grade printing (600dpi or more) | 77 | m | 2013 |
| Widespread use of battery-free, non-contact smart IC cards or RF-ID (radio frequency identification) TAG for use in navigation for visually impaired people, medical care cards, goods distribution TAG, etc | 75 | h | 2011 |
| Practical use of an automatic automobile driving system using GPS with a resolution capability of 10cm or less | 74 | m | 2014 |
| **Information and Communication** | | | |
| Widespread use of highly reliable network systems capable of protecting the privacy and secrecy of individuals and groups from the intrusion of illintentioned network intruders | 93 | m | 2010 |
| Realization of an environment in which the unlimited utilization of highcapacity networks (150 Mbps) for around 2,000 yen/month or less is possible | 92 | m | 2009 |
| Advances in software inspection and verification technology, enabling error-free, large-scale software to be developed in a short period of time | 89 | l | 2019 |
| Practical use of integrated building management systems and home security systems which are linked to an earthquake detection system, and take advantage of the time delay to the arrival of seismic waves from a non-direct-hit earthquake to initiate the necessary safety measures to protect human life | 88 | m | 2016 |
| Widespread use of online seal-free (signature-free) document preparation services for various official documents such as contracts which are provided via a network based on security technology capable of achieving both privacy protection and verification | 86 | m | 2010 |
| Widespread use of systems which facilitate multimedia communication from anywhere in the world using pocketbook-size portable terminals | 85 | h | 2008 |
| The number of recycled parts in new personal computers, including displays, exceeds 90% of all component parts | 84 | l | 2012 |
| Development of an optical transmission system capable of high-volume transmission of 1 Peta bps per optical fiber | 82 | m | 2013 |
| Widespread use of a SCM (supply chain management) system to handle data management (orders, design, manufacturing, operations, and maintenance) uniformly among related companies | 81 | l | 2008 |
| Development of a super high-speed computer communication protocol capable of achieving a throughput of tens of Gbps | 81 | h | 2009 |
| Development of technology capable of automatically detecting viruses and automatically producing corresponding vaccines | 81 | l | 2013 |
| Widespread use of mobile communication terminals with a communication speed of 30 Mbps when used outdoors | 80 | h | 2011 |

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| Widespread use of portable terminals capable of voice communication from anywhere in the world | 80 | h | 2007 |
| Widespread use of a security technology that automatically monitors illicit activities involving network ethics, such as copyright infringement concerning multimedia software use over a network and the violation of privacy | 79 | l | 2012 |
| Realization of a more paperless and efficient office environment in a majority of companies regardless of size through a steady shift to electronic and network processing for most office work | 79 | h | 2011 |
| Widespread use of government office services through networks regarding applications and general procedures | 79 | l | 2009 |
| Practical use of optical switching equipment that switches light signals as light without converting them into electronic signals | 77 | h | 2011 |
| Development of browsers with a multilingual automatic translation function that enables users to read in their own language most web pages written in other various languages | 76 | l | 2011 |
| Widespread use of low-energy personal computers capable of running for one full year on a single button-type battery | 74 | h | 2016 |
| Widespread use of electronic money for cash transactions to the extent that it has the same feeling as using conventional money | 74 | h | 2013 |
| **Materials and Processing** | | | |
| Practical use of systems for the genetic diagnosis and treatment of cancer and incurable diseases based on genome analysis | 90 | h | 2014 |
| Practical use of large-area amorphous silicon solar cells with a conversion efficiency of more than 20% | 89 | l | 2016 |
| Practical use of multi-layer solar cells with a conversion efficiency of more than 50% | 89 | h | 2019 |
| Development of superconductors with a transition point at room temperature or higher | 87 | h | 2022 |
| Practical use of carbon dioxide fixation technology necessary for protecting the global environment | 85 | l | 2019 |
| Practical use of hydrogen production processes for water decomposition by sunlight | 85 | m | 2019 |
| Development of three-dimensional cumulative processing technology of nanometer scale | 85 | h | 2016 |
| Practical use of memory chips with a capacity of 1 terabit | 84 | h | 2016 |
| Widespread use of recycling systems for general-purpose plastics, allowing recycled goods to account for at least 30% of total production | 84 | l | 2015 |
| Widespread use of polymer synthesizing processes that use renewable resources instead of conventional petrochemical processes | 83 | l | 2019 |
| Widespread use of signal-responsive missile drugs capable of efficiently reaching targeted parts such as tumor cells | 82 | h | 2013 |
| Practical use of low-temperature catalytic processes for producing hydrogen directly from methane | 80 | m | 2015 |
| Practical use of single electron memory elements | 79 | h | 2020 |
| Development of devices that utilize switching functions of a single molecule/atom | 79 | h | 2018 |
| Practical use of rechargeable polymer batteries having a volume-specific capacity of 500 Wh/liter (Capacity of current Ni-Cd batteries: 250 Wh/liter) | 78 | h | 2013 |
| Practical use of industrial methane hydrate mining technology | 78 | l | 2019 |
| Widespread use of superconductive material with a working temperature equal to liquid nitrogen (77 K) or higher | 76 | m | 2016 |
| Practical use of technologies for utilizing cultured tissue from stem cells or ES cells as material for artificial organs or tissue | 75 | l | 2016 |
| Development of synthesizing plastics directly from $CO_2$ and water using light as the energy source | 75 | h | 2022 |
| Practical use of insulating material for VLSI with a permittivity of 1,3 or less | 73 | m | 2012 |

*** Abbreviations:**

- Imp. Ind.: Importance Index (arbitrary units)
- Nano Rel.: Nanotechnology Relevance: h= high, m= medium, l=low (Source: VDI-TZ)
- time: Forecasted realization time