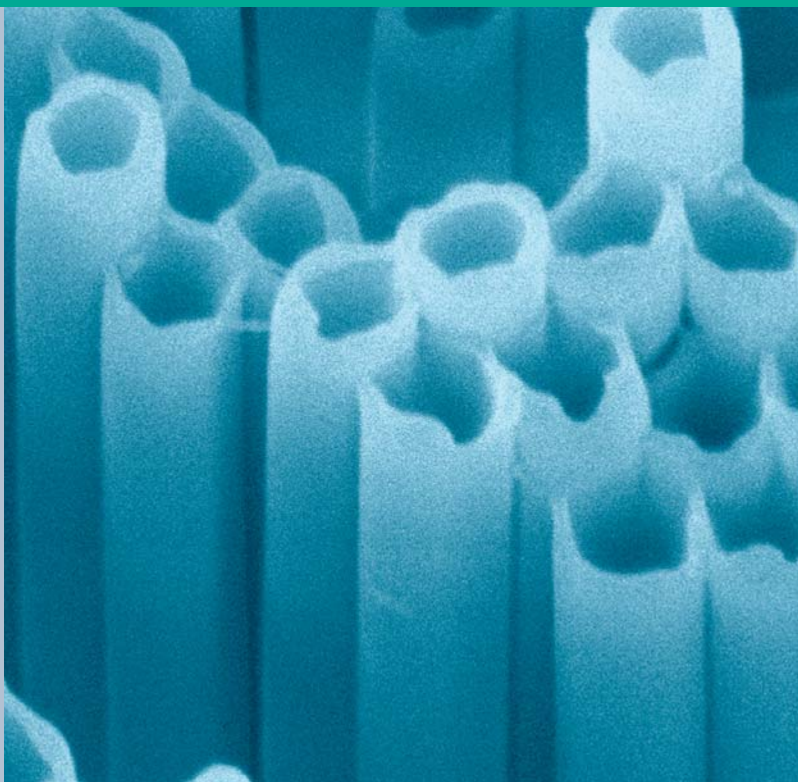
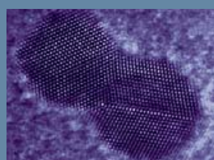
Hessian Ministry of Economics, Transport,
Urban and Regional Development

HESSEN

Uses of Nanotechnology in Environmental Technology in Hessen

Innovation potentials for companies





hessen »
Hier ist die Zukunft

nanotech
umwelttech

www.hessen-nanotech.de
www.hessen-umwelttech.de

Uses of Nanotechnology in Environmental Technology in Hessen

Innovation potentials for companies

Volume 1 of the occasional Paper Series
of the Aktionslinie hessen-nanotech

Imprint

Uses of Nanotechnology in Environmental Technology in Hessen – Innovation potentials for companies

A brochure for small and medium-sized companies from the Hessian Environmental Technology and Hessian Nanotechnology initiatives of the Hessian Ministry of Economics, Transport, Urban and Regional Development

prepared by:

Daniel Heubach
Severin Beucker
Claus Lang-Koetz
Fraunhofer-Institut für Arbeitswirtschaft
und Organisation IAO
Nobelstraße 12
D-70569 Stuttgart

IAO
Fraunhofer Institut Arbeitswirtschaft und Organisation

Editors:

Dr. Rainer Waldschmidt, Maria Rieping (HMWVL)
Dr. Carsten Ott, Alfred Stein, Sabine Wesche
(HA, hessen-umwelttech)
Alexander Bracht, Markus Lämmer
(HA, hessen-nanotech)
Editorial offices Frantz, Göttingen

Publisher:

HA Hessen Agentur GmbH
Abraham-Lincoln-Straße 38-42
D-65189 Wiesbaden
Telephone 0049 (0) 611 774-8614
Fax 0049 (0) 611 774-8620
Internet www.hessen-agentur.de

The publisher gives no guarantee on the correctness, the accuracy or the completeness of the information or for the respect of the intellectual property rights of third parties. The views and opinions expressed in the publication are not necessarily those of the publisher.

© Hessian Ministry of Economics, Transport,
Urban and Regional Development
Kaiser-Friedrich-Ring 75
D-65185 Wiesbaden
Internet www.wirtschaft.hessen.de

Reprinting and reproduction in whole or in part is not permitted without prior written permission.

Translation: Kubus Translations
Layout: WerbeAtelier Theißen, Lohfelden
Printing: Werbedruck Schreckhase, Spangenberg
Cover photograph: Bundle of nanotubes
(Source: Philipps-Universität Marburg)

www.hessen-umwelttech.de www.hessen-nanotech.de

Environmental technology meets nanotechnology –

because success thrives on innovation!

German companies have always held a leading position in environmental technology. Hessian companies are right at the forefront and are supported by the Hessian Environmental Technology initiative of my Ministry. Nevertheless, Hessen cannot rest on its laurels. In these times of constantly growing and changing markets, a key to success is in research and the use of innovative technologies.

One of the most important new technologies of this new century is nanotechnology. The selective use and influencing of physical and chemical properties can lead to nanotechnological innovations which can affect all spheres of our lives in the form of new products. All nanotechnology sectors are being intensively researched in Hessen. The Hessen NanoNetwork of Hessian Universities founded in 2004, together with our Hessian Nanotechnology initiative and our Technology Transfer Network (TTN-Hessen), are supporting Hessen universities by encouraging collaboration with Hessen enterprises. Leading companies are already working as providers or users of nanotechnology.

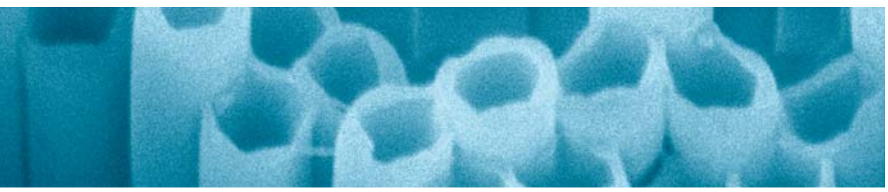
Despite this, a business survey carried out by my Ministry among more than 6,000 Hessian enterprises has shown that the potential of nanotechnology is not yet sufficiently well understood.

Thus, true to the motto "Support strengths", we aim to integrate our existing strengths in nanotechnology in Hessen with the prominent market position of environmental technology businesses. The small and medium-sized environmental technology companies in Hessen serve as the lynchpin and are a key element in the value chain. Their power of innovation and their detailed understanding of the market are the levers we can and should use. It is only by working closely with small and medium-sized enterprises that Hessen can continue to assume a strong position against international competition.

The present brochure is intended as a help towards achieving this aim. I hope that we can arouse your interest in nanotechnology and thus encourage the development of new environmental technology products based on nanotechnology.

Dr. Alois Rhiel
Hessian Minister for Economics, Transport, Urban and Regional Development

Contents



Summary

Nanotechnology is distinguished by the functionalities and properties of components and materials which are dependent on effects in the nanometer range (10^{-9}m)

Nanotechnology will be among the key technologies of the twenty-first century. It is distinguished by the functionalities and properties of components and materials which are dependent on effects in the nanometer range (10^{-9}m). Nanotechnology aims to tailor and design nanoscale structures with defined functionalities. This includes, for example, mechanical, chemical or geometric properties of particles or surfaces which are used in product systems.

It is expected that nanotechnology will influence practically all industrial sectors in the medium term. The possible applications range from optimisation of existing products and processes to product innovations up to revolutionary new production concepts. Nanotechnology will thus influence all areas of social life. However, many nanotechnological applications are currently still in the research stage, and even more research and development work is needed for numerous applications. Nevertheless, the first product innovations have already found their way on to the market (see Figure 8, page 16). For example, TiO_2 nanoparticles are used for UV-protection in sun creams, or nanoparticles in scratchproof car paints, and nanothreads are being used to optimise new filter systems.

As of today, environmental technology has not been a direct driving force in nanotechnology research. However, due to the characteristics of nanotechnology, many technological innovations in environmental technology are conceivable: Mechanical, chemical, and biological functionalities and the geometric properties of nanotechnology can be used in many environmental technology applications, e. g. in filtration, sensors, catalysis, or in energy systems (see Table 2, page 26).

Environmental technology may also benefit from a range of "indirect" nanotechnology application areas. These include surfaces with proven environmentally friendly easy-to-clean properties.

In this way, nanotechnology can support environmental technology companies and lead to new product innovations where:

- physical-chemical methods / processes play an important role and where a particularly large surface / volume ratio has a strong influence on the process,
- the products are based on biological methods / processes, particularly at the interface between biological and technical components,
- the design and functionalisation of surfaces or boundary surfaces are very important and their influence improves the product value, or
- further miniaturisation or compact systems (e. g. sensors and energy supply) will be required.

What are the following steps?

If one or more of these aspects is of importance for a company's product or processes, the next step would be to analyse in detail what "nanofunctionality" *(see Chapter 3.3)* could be used to enhance product value and how the new technological properties would fit in with established technologies *(see Chapter 3)*.

To estimate the use potential, the company could widen its knowledge by searching the technological literature and the internet, analysing patents or contacting research and technology transfer organisations in Hessen *(see page 49)*.

Surveys in the context of this brochure have shown that nanotechnology is still largely unknown in the environmental technology sector. At present, nanotechnology research is strongly driven by technical possibilities while environmental technology is problem-oriented. Both approaches need to be merged in order to develop innovative products and services – the potential is there.

Hessen is well-positioned in both nanotechnology and environmental technology. All nanotechnology sectors are being researched to a high international level in Hessen and well-known companies are active in the nanotechnological field. In environmental technology, Hessen is particularly well placed in the following fields: water / wastewater, waste, energy / clean air / climate protection, analysis / measurement and control technology, and integrated product policy. Thus all the necessary facilities are available to advance research in the overlapping areas of nanotechnology and environmental technology and to put them to practical use. This makes a valuable contribution to environmental protection and at the same time strengthens the Hessian economy.

The present brochure demonstrates the innovative potential of nanotechnology for environmental technology companies in Hessen. It starts out with a introduction to nanotechnology and its various functionalities on the basis of which the application potential in environmental technology can be assessed. The application potential is then set against the facilities already available in Hessen's nanotechnology sector. Examples of possible uses for nanotechnology are provided by selected environmental technology applications in filtration, pollutant decomposition, catalysis and sensors. The brochure ends with an account of the innovative potential of nanotechnology from the point of view of technology management and demonstrates approaches for effective technology transfer of nanotechnology to environmental technology.

For a fast overview:

What's new in nanotechnology?

- Chapter 1.2, page 9
- Figure 5, page 9

What can nanotechnology do?

- Chapter 1.3, page 12

What applications already exist and what are still to come?

- Chapter 1.4, page 14
- Figure 8, page 16

What are possible applications for environmental technology?

- Table 1, page 20 / 21
- Table 2, page 26

What concrete applications are there already in environmental technology?

- Chapter 2.4, page 29

How should environmental technology companies proceed?

- Chapter 3, page 34

What contacts are available in Hessen?

- Information & addresses, page 49

Introduction – why this brochure?

Nanotechnology will be among the key technologies of the twenty-first century *(Bierhals 2000, BMBF 2002, VDI 2004/2)*. It is important to understand the new functionalities and properties of materials and elements at the molecular level which are strongly dependent on the nanoscale effects of their components. Examples of such nanoscale effects are chemical surface properties which result in new catalytic or adsorption functionalities of materials. For example, a nanostructured surface provides a layer which is not wetted either by water or by oil (ultraphobic) and to which liquids and dirt do not adhere *(see the Lotus effect in Figure 1 as an example)*.

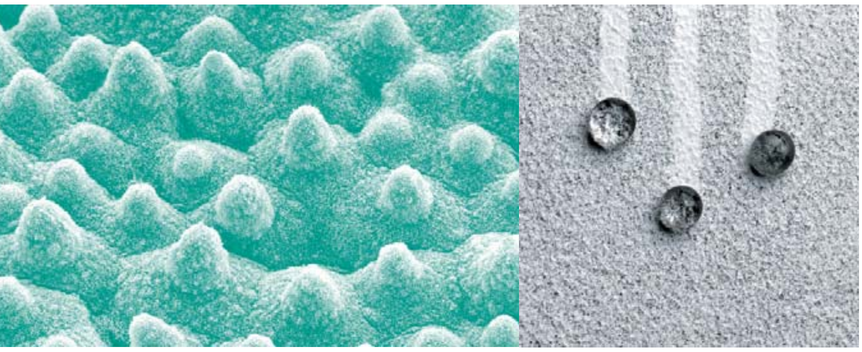


Figure 1:

Left: A double structured biological surface optimised for self cleaning. Contact surfaces are minimised by the combination of microstructure (cells) and nanostructure (wax crystals) *(Source: Professor Wilhelm Barthlott, University of Bonn)*.
Right: Lotusan® exterior paint which cleans itself with rain through the Lotus-Effect® *(Source: sto AG)*

Nanotechnology is not a product or a process – it describes new discoveries about material properties and structure in the 10^{-9}m dimension. The combination of these findings with existing conventional products or technologies opens up completely new perspectives. These extend not only to the product and its application areas, but also to the engineering of products. However, before analysing possible uses of nanotechnology in environmental technology, it is important first of all to understand the effects and potentials of both technologies. Only in this way it is possible to make deliberate use of the properties of nanomaterials, integrate them at the macroscopic level and fit them together to form new, complex product systems *(Figure 2, page 7)*.

Environmental technology – like nanotechnology – is an interdisciplinary work field, which sets out to solve environmental problems in the separate environmental media. The media-related areas of application for environmental technology offer numerous opportunities for the use of nanotechnology. Nanotechnology can help to provide solutions for future water and energy supply problems. Filter systems, solar and fuel cells, and water treatment (e. g. sea water desalination) are research areas with great market potential.

Environmental technology is forecasted to have a world wide market size of 750,000 million Euros by the year 2010, which corresponds to an average annual growth of eight percent. Its usage and growth potential thus make environmental technology an attractive field of application for nanotechnology. The export of innovative environmental technology therefore provides considerable opportunities for companies in Hessen. Environmental technology may also benefit from nanotechnological innovations in the areas of material techno-logy, process technology, biotechnology, microtechnology, or information technology.

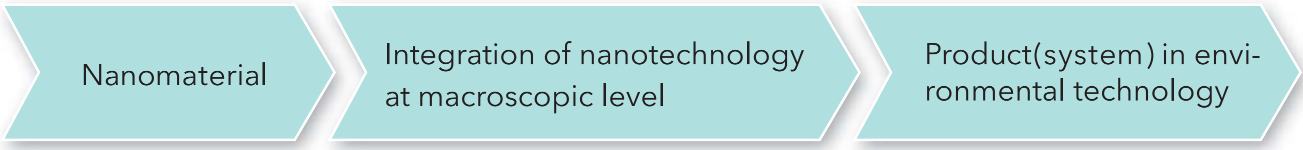


Figure 2: Value chain and integration of nanotechnology

This includes, for example, energy efficient lighting systems, sturdier and lighter materials, significantly improved chemical and biological sensors or specific surface properties.

As in many other sectors, the practical use of nanotechnology in environmental technology is just at the beginning of its possibilities. On the one hand, this is because there is still research and development work to be done in many areas of nanotechnology. On the other hand, basic nanotechnology effects are still not known to many users and manufacturers of environmental technology.

Where and how can nanotechnology also be used in environmental technology? How can the innovative potential of nanotechnology be made known to an interested audience in the field of environmental technology and thus contribute to creating market advantages for environmental technology companies? This brochure provides answers by showing the innovation potential of nanotechnology for environmental technology and by highlighting many promising application areas.

For the preparation of this brochure, a select group of nanotechnology and environmental technology experts were asked to give an account of their experience. Their statements, which have been incorporated anonymously into the texts and conclusions of the brochure, give an idea of the current state of nanotechnology and its possible uses in environmental technology in Hessen.

Structure of this brochure

- Chapter 1:
  Introduction to nanotechnology
- Chapter 2:
  Application potential and application areas of nanotechnology in environmental technology
- Chapter 3:
  Innovation potential and approaches to technology transfer
- Appendix:
  Research programme and assessment of market technology impact
- Information & addresses

1 Introduction to nanotechnology

1.1 Definition of nanotechnology

Definition: "Nanotechnology deals with systems, the functionalities and properties of which are exclusively dependent on the nanoscale effects of their components"

Nanotechnology[1] is based on the perceptions and possibilities of specifically and consciously influencing the properties and structures of materials at the supramolecular level. Thus it is possible to functionalise, miniaturise or specify materials and surfaces in order to improve, for example, their chemical selectivity.

Therefore, nanotechnology is neither a single scientific discipline nor a defined application area. Its order of magnitude may be used as a definition. Thus, nanotechnology deals with systems, the functionalities and properties of which are exclusively dependent on the nanoscale effects of their components *(Bachmann 1998)*.

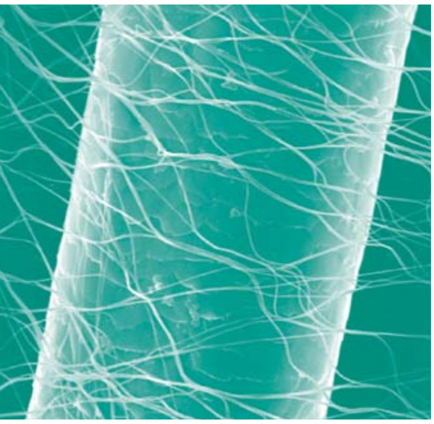


Figure 3: Nanofibres (horizontal) compared to a human hair (vertical) under an electron microscope *(Source: Philipps-Universität Marburg)*

The influencing of structures less than 100nm in size is considered to be one of the working areas of nanotechnology *(see size comparison in Figure 3)*. The following effects are essential and functional aspects of nanotechnology and are of particular importance from the point of view of environmental technology:

- **Size effects:** The progressive miniaturisation into the nanoscale range enables new application areas and the implementation of functionalities in the smallest space[2].
- **Structure effects:** With the understanding and conscious construction of structures, it should be possible to influence the properties of materials at their very base and to use and integrate them into complex combined systems[3].
- **Surface effect / boundary surface effect:** The design of structures at the molecular level and the increasing surface / volume ratio has effects on the boundary surface of materials and particles. The surface of a material and its properties can become an important product function *(see Figure 4, page 9)* by enlargement and functionalisation of the boundary surface.

---

1 The description "nano" is derived from the order of magnitude of the range under consideration, the nanometer (nm = 10^{-9}m). The word "nano" comes from the Greek and means "dwarf".

2 The American, Richard Feymann (1918–1988), professor in theoretical physics, who received the Nobel Prize in 1965 for his work in the field of quantum electrodynamics, pointed out the unlimited possibilities for miniaturisation: "There is plenty of room at the bottom". In the atomic dimension, there would be enough room to store the complete knowledge of humanity on the head of a pin *(Hullmann 2001 and Bachmann 1998)*.

3 The basic concept of building up a large system from small parts (considered as single atoms or molecules in nanotechnology) is described as the "bottom-up approach". In contrast, the "top-down approach" describes the creation of small structures from larger units, as lithography methods in microelectronics.

1.2 Innovation potential of nanotechnology

Engineering perceptions and understanding change in the nanometer range

Working in the nanometer area also changes engineering considerations and understanding: Quantum mechanics takes the place of classic continuum physics. Surface effects and the molecular properties of materials dominate instead of macroscopic effects, e. g. mechanical effects.

One nanoparticle with a diameter of 3nm contains approx. 800 atoms. More than 30 percent of these are on the boundary surfaces *(see Figure 4 for an illustration)*. The surface atoms have high reactivity as they generally have unsaturated bondings. In this way, the chemical properties – such as the catalytic activity – of the particles are decisively influenced.

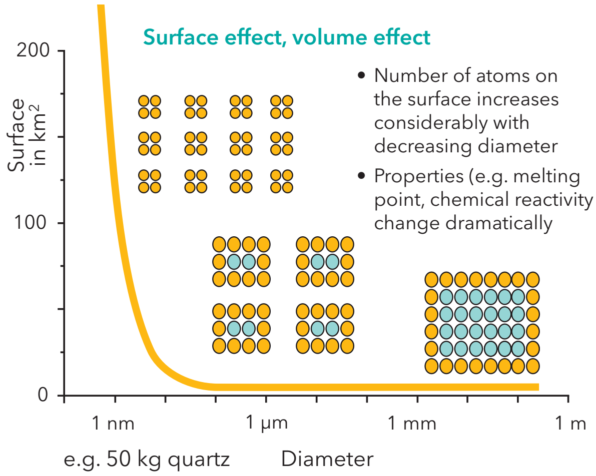
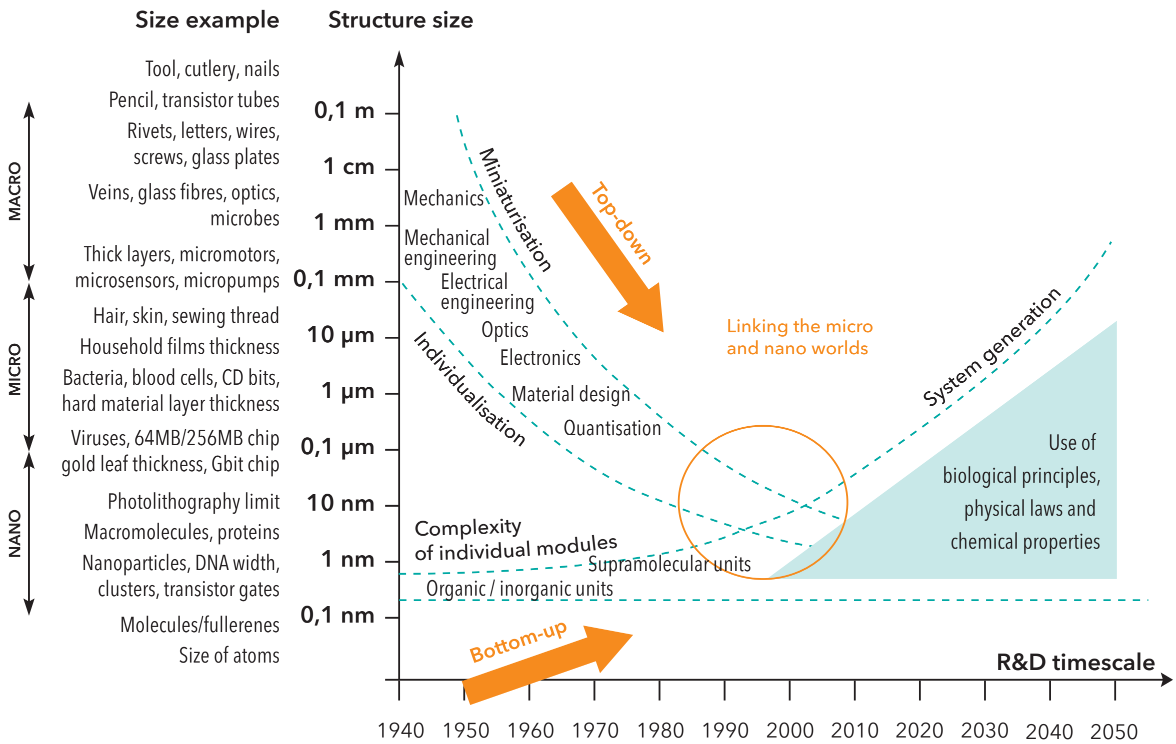


Figure 4: Example of the dependence of the material surface on the particle diameter (for constant total volume or constant total mass)

Exploration of the nano range is possible only by an interdisciplinary combination of physics, biology and chemistry. At the same time there are two design approaches which are clearly emerging from nano research and which can show new potential for environmental technology *(Figure 5)*. According to the "top-down" approach, miniaturisation is driving microtechnology more and more strongly into the nanoscale order of magnitude while the specific structure build-up at the molecular level depends on the "bottom-up" approach, e. g. by self-organisation, and results in the planned construction of molecular structures and properties.

Figure 5: Linking the micro and nano worlds and design approaches *(Bachmann 2004)*



The properties of macroscopic structures can be specifically adjusted through controlled construction using atomic and molecular components (bottom-up). The understanding of the molecular basics of new materials is opening up new perspectives, among which is the manufacture of "switchable" materials which can, for example, acquire polar and non-polar properties. The so-called Carbon Nano Tubes *(CNT, Figure 6)* are a nanomaterial offering considerable potential. They can be used both as conductors and as semiconductors.

The combination of physics, biology and chemistry offers considerable changes in properties and new functionalities

Considerable modifications of material properties are possible due to the combination of physics, biology and chemistry which decisively determines the functional properties of nanotechnology *(Bachmann 2004)*. Here are a few of the properties which could be of use to environmental technology companies:

- The enlarged surface of nanomaterials is making **new chemical processes** possible by modification of melting and boiling points, chemical reactivity and catalytic yield. For example, nano-iron particles are being used for reduction of pollutants and in water purification. Nanoscale zeolites can be used in environment analysis or for oxidisation in cation exchangers; titanium dioxide particles can be used as nanoparticles in the photocatalysis of organic contamination or metal organic frames as nanocubes for hydrogen storage.
- Quantum mechanical behaviour is leading to a **new technical physics** of particles and materials, e. g. by changing colour, transparency, hardness, magnetism, or electrical conductivity. Conductivity plays an important role in the proton exchanger membrane (PEM) of a fuel cell or in chemical sensors for gas analysis. Nanoscale particles are often suitable for high transparency requirements and at the same time provide new properties such as thermal insulation or a self-cleaning effect.
- This molecular recognition results in **new bioapplications** which use biological modules, resort to principles of natural functions, support biotechnological processes or manufacture biocompatible and biofunctional materials *(TAB 2004)*. For example, biologically reactive nanostructures can be installed on a support as biosensors.

(*Source top*: BASF AG, Ludwigshafen)
(*Source centre*: Institut für Physikalische Chemie, Universität Hamburg)
(*Source bottom*: Max-Planck-Institut für Biochemie / Peter Fromherz)

The objective is higher specifications, selectivity and functionalisation through nanotechnology

A great deal is expected from the new material properties identified in nanotechnology with regard to specification, selectivity and functionalisation as well as for the design of particles, materials and components.

The ideas of Eric Drexler[4] can be viewed as a less realistic future scenario. He represents the vision of machine construction at the nanometer level, also called molecular nanotechnology, and describes nanorobots which replicate themselves and can also manufacture material themselves[5]. Many other researchers take a more realistic view. They consider that nanotechnology will not only design products and processes more efficiently in the short term, but will also lead to new applications and functions (e. g. cancer therapy or data storage media).

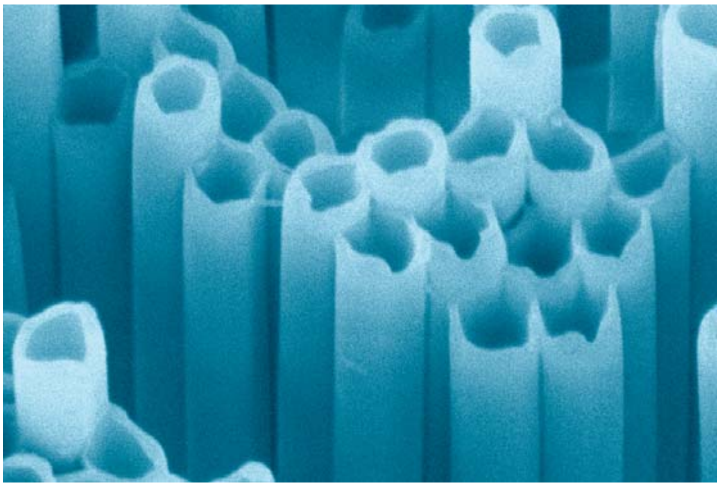
The major potential of nanotechnology, which is also important for environmental technology, is mainly based on *(see Bachmann 1998)*

- the **miniaturisation** of structure sizes and systems. The large surfaces of small particles can be used in catalytic processes.
- the **use of the revolutionary principles of self-organisation or replication**. The goal is the construction of supramolecular functional units or biological macro molecules. Examples of these are sensors based on principles of natural functions, or surfaces which form during the organisation process and result in specific physical-mechanical or chemical properties such as surfaces offering corrosion resistance or low friction.

The experts see positive effects and possible uses for nanotechnology in the areas of environment and health, for example the development of new methods for diagnosis and therapy or new drugs and agrochemical products. Environment-friendly effects are expected from savings in resources or increases in energy use efficiency. Possible energy savings through the increased use of LEDs with nanotechnology, such as white LEDs for general lighting in Germany, are equivalent to the output of two nuclear power stations *(Bachmann 2004)*.

The further development of tools and technologies for measuring and manipulation will be a key task for mastering structuring and manufacturing methods in the nanoscale range, because the resolution of the smallest nanoscale structures will require further research and development at these orders of magnitude.

Figure 6: Bundle of carbon nano tubes
(*Source:* Philipps-Universität Marburg)



4 Researcher and the President of the Foresight Institute, USA (www.foresight.org/FI/Drexler.html).

5 Engines of creation The Coming Era of Nanotechnology, Eric Drexler, 1986, and Unbounding the Future: The Nanotechnology Revolution by Eric Drexler and Chris Peterson, William Morrow and Company, Inc., New York 1991.

1.3 Functionalities of nanotechnology

With its wide range of effects and functionalities, nanotechnology is theoretically suitable for use in almost all sectors and technologies – including environmental technology. Unlike other technologies, such as biotechnology, it cannot be defined satisfactorily in terms of its areas of application.

In addition, research in nanotechnology is still largely driven by the possibilities of new materials and methods ("technology push") rather than by concrete, customer-oriented applications ("market pull"). Until now, practical applications have in many cases been identified more by chance than by design.

> *The functionalities are the key to the application-oriented approach in nanotechnology*

The functionalities identified for nanotechnology materials, products and processes provide a good application-oriented access to nanotechnology for business. These phenomena are closely associated with product utilisation and function and thus with customer-oriented demand, and forge the link between nanotechnology and environmental technology. The functionalities are introduced below *(according to TAB 2004)*.

Mechanical functionalities

The clearly improved mechanical functionalities of nanostructured solid bodies offer increased hardness, break resistance and toughness at low temperatures or super plasticity at high temperatures. The basis for these effects is a reduction in granular size, the grains being reduced to a size below which no further plastic deformation can take place. For customers, this offers advantages such as extended service lives for production tools and components, or resource-efficient lubrication systems.

Special geometric characteristics

The special geometric characteristics of nanostructures lie in their space requirement at the order of magnitude of atoms and molecules *(see Figure 4)*. This results in atomic precision and extremely large surface/volume ratios of nanoporous and nanoparticle materials. Customer benefits include adjustable pore sizes of nanoporous membranes, molecule specific separation and selective catalysis or load separations and adsorption in environmental technology processes.

Electrical functionalities

The reduction of the particle size and the layer thicknesses in the low nm-range results in the development of additional electronic conditions. An electron can only accept discrete, separate energy levels separated by gaps. Such particles do not behave like solid bodies, but instead are similar to atoms. They can be customised with regard to their electronic and optical properties by deliberate influencing the structure. One practical use of this effect is in elements with switchable electrical statuses, optical switches, thermoelectric materials such as heat exchangers or antistatic surfaces.

Magnetic functionalities

The magnetic functionality in the nm-range is based on paramagnetic and ferromagnetic properties of solid bodies. The macroscopic magnetic properties can be influenced and paramagnetism occurs, described here as superparamagnetism. In practice, the magnetic resistance effect (MR effect) is used and is applied in magnetic field sensors, magnetic storage elements (Magnetic RAM, MRAM), or adhesives which are modified with nanoparticles in such a way that the adhesive properties become switchable.

Optical functionalities

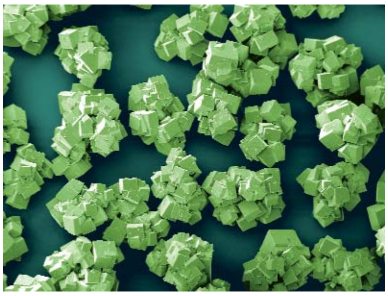
The optical functionalities are based on the fact that the nanoparticles are clearly smaller in size than the wavelength of visible light: they give off no reflection. By customising their size, it becomes possible to obtain a sharply limited, specified wavelength range (one colour) in which the material absorbs or emits light. Nanoparticles reveal new optical properties with regard to colour, fluorescence or transparency. This is used in transparent dispersions of nanoparticles or in optically functional surfaces such as, for example, the antireflection coating of solar cells, or in the area of optical analysis and information transfer.

Chemical functionalities

The chemical functionality of nanoobjects is based mainly on their surface structure: Nanostructured materials exhibit a considerably large proportion of surface atoms *(see Figure 4, page 9)*. Such atoms are particularly reactive due to their unsaturated bondings. Lattice hardening or a distorted bonding angle result in a significantly enlarged surface energy. This is useful for surfaces with customised wetting behaviour, for spatial arrangement of functional groups, for enhanced chemical selectivity and reactivity, as well as chemical stability in various chemical processes.

Biological functionalities

The biological functionality of nanoscale materials is understood to mean the interaction with complex biological systems such as cells, organisms or biomolecules. An essential element here is the roughness and structuring in the micro- and nanometre range. Practical uses arise from the "Nano2Bio" transfer direction, i. e. the use of nanotech processes and materials for studying biological issues, e. g. in nanoanalysis. At the same time, the "Bio2Nano" transfer direction offers the opportunity to use biotechnology materials and construction plans for manufacturing technical nanosystems – biological modules are used in the nanoscale as components for technical systems. The basis for these is provided by biological modules, functional or organisational principles.



1.4 State of research and practical application

Practical application of nanotechnology varies widely from one area of technology to another *(Hullmann 2001, Bachmann in VentureCapital 2002)*. However, in all application areas there are new materials or products which build on nanotechnology *(see Figure 8)*. These range from nanooptimised layers on electronic components such as the GMR sensors (Giant Magneto Resistance) and nanomembranes to new processing and analysis methods. The latter also represent the basis for further work in nanotechnology.

The commercial use of nanotechnology materials and base materials to date has already been carried out on a considerable scale for a range of well-researched materials, e. g. titanium dioxide (TiO_2) in paints or sun protection equipment, and Carbon Black for car tyres. A world market value of 8,000 million US$ is estimated for Carbon Black in 2006 and a value of 1,200 million Euros is expected for Carbon Nano Tubes (CNT) *(VDI 2004/2)*. The first concrete application areas are also emerging for CNTs in composite materials. Electrically conductive paint with CNTs in electrostatic spray painting is expected to save paint and solvents. The research into basic mechanisms and principles in the nm range is the starting point for systematically developing the potential of new materials.

According to indicators, the market potential of nanotechnology will be 100,000 million to 1 billion US$ by the year 2010 *(VDI 2004/2)*. The spread reflects the uncertainties still present with respect to realistic estimates of the market volume. The reasons for this are the cross-sector character of nanotechnology, classification problems with sales figures and the early development phases in some areas. However, there is unity about the enormous economic potential of nanotechnology in the twenty-first century.

Examples of nanotechnology applications

The first applications of nanotechnology are already on the market

The first applications of nanotechnology are already available on the market. For example, these include *(see TAB 2004)*:

- Nanosize titanium particles as UV protection in sun creams,
- Scratchproof varnishes for automobiles (e. g. Daimler-Chrysler) and coatings with Lotus effect (e. g. Lotusan® from sto AG, *see Figure 1, page 6*),
- Nanoparticles made of platinum, rhodium and palladium in vehicle exhaust catalytic converters and fuel cells,
- Iron oxide pellets with a nanostructured surface for adsorption of arsenic in drinking water purification (Product Bayoxide® E33),
- Nanostructured Carbon Black particles as filler material in car tyres,
- Copper nanoparticles as an additive in lubricants to reduce wear,
- Impregnation and cleaning agents with nanotechnology for better dirt repulsion and with an anti-tarnish function,
- Electrochrome layers with nanotechnology for controlled darkening of mirrors and as an anti-reflection coating in instrument clusters or displays *(see Figure 7)*.

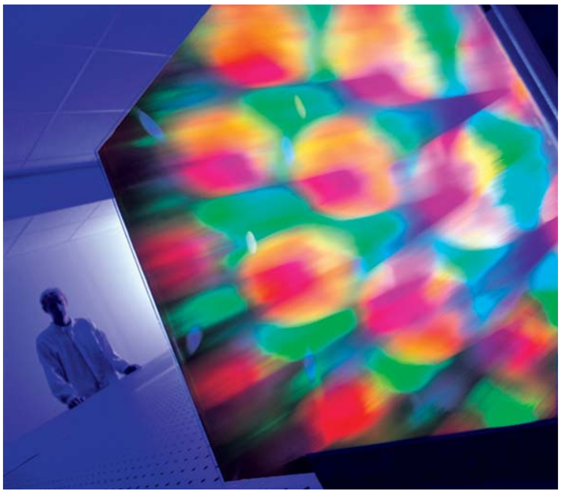
These examples clearly show that nanotechnology until now has been mainly implemented to optimise existing products in areas of conventional technology such as car manufacturing or the electronics industry and has not yet resulted in revolutionary new products or applications. However, it is expected that by 2015, nanotechnology will have penetrated and influenced almost every branch of industry *(VDI 2004/2)*.

State of development

Figure 8 gives an overview of the state of development of selected application areas of nanotechnology in different branches of industry.

Nanotechnology is expected to be used in environmental technology initially in membranes, solar cells, and hydrogen storage

According to a summary by Bachmann *(Figure 8, Bachmann und Rieke 2004)*, from the point of view of energy and environmental technology, the greatest application potential of nanotechnology is anticipated in membranes, solar cells and hydrogen storage. Nanomembranes are already used today for cleaning wastewater.



Dye sensitised solar cells with an efficiency of approx. eight per cent are currently in the prototype stage. Numerous economic application areas are conceivable for them, for example in the form of electronic price labels with an integrated dye sensitised solar cell module *(Hinsch 2004)*.

Hydrogen storage based on Carbon Nano Tubes or metal oxides and alloys and organic bondings such as nanocubes *(Altmann 2004)* can open up new opportunities in the future for integrating fuel cell technology with a corresponding hydrogen storage medium in small devices such as mobile telephones, digital cameras, PDAs, or laptops. Nanostructured hydrogen storage and quantum point solar cells are still at the prototyping or research stages.

Experts see the following challenges and opportunities for the future research and commercialisation of nanotechnology:

- Achieving significantly improved product features at similar or lower costs,
- dealing sensitively, sophisticatedly and as soon as possible with the potential risks of the technology in order to avoid public non-acceptance, as in the case of gene and biological technology,
- bundling competences and research promotion in the most promising economic areas, and
- establishing nanotechnology as a seal of quality for High-Tech research and innovative products.

Figure 7: Nanostructured surface as anti-reflecting surface or for high-contrast displays
(*Source*: Fraunhofer ISE / Bernd Müller)

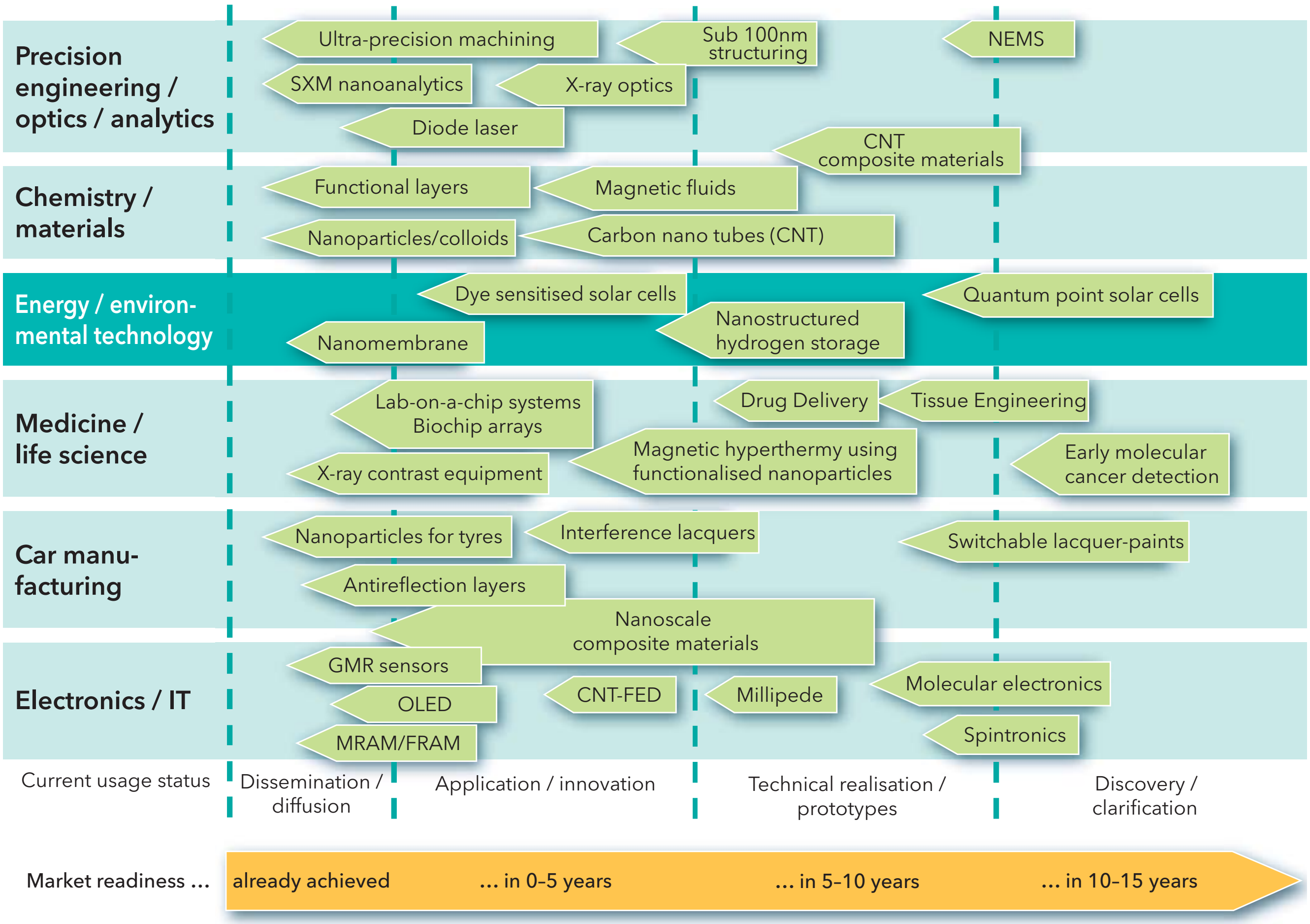


Figure 8: Current state of development of individual nanotechnologies according to application sectors and time period until expected readiness for market (*Bachmann und Rieke 2004*)

Nanotechnology research

Germany has a leading international position in nanotechnology research

Germany is in third place worldwide after the USA and Japan for nanotechnology research and thus has a leading international position *(TAB 2004)*. Whereas Japan is better than Germany in putting technological developments into practical use, Germany has a higher competence in research *(Hullmann 2001)*. Germany also has a leading position with respect to publications and patents[6]. Taking account of the quality of patents in the various countries, Germany is at least equal to the USA and significantly ahead of Japan *(VDI 2004/2)*.

Stakeholders in Hessen

> *Hessen is represented in all sectors of nanotechnological research*

An inventory of the material based technologies in Hessen shows that Hessen is represented in all sectors of nanotechnology research by universities. In addition, approximately 250 companies in Hessen have been identified as being active in the areas of material and surface technology, microsystem technology and optical technologies, of which more than 70 companies develop and provide or use nanotechnologies *(FEH 2004, HA 2005)*.

Contact persons and organisations for nanotechnology and environmental technology in Hessen and the nanotechnology competence networks in Hessen are listed in the Appendix *(see pages 49/50)*. The universities of the recently founded NanoNetzwerk Hessen (NNH) and their contact persons are listed separately on page 50. Page 51 shows the university nanotechnological research in Hessen by subject. Page 52 gives an overview of the Hessian stakeholders in the nano competence centres of the Federal Ministry of Education and Research (BMBF).

1.5 Research programmes and market

To date, promotional measures by the public authorities have been the most important impetus for nanotechnology research. Many states have introduced their own promotional programmes which promote separate nanotechnology research areas; at the same time, research activities are often also coordinated by the state. In the USA, more than 800 million Euros were provided for nanoresearch in 2004; in Germany it was just under 300 million Euros with which the Federal Ministry of Education and Research (BMBF) and the Federal Ministry of Economics and Labour (BMWA) promoted projects and institutions *(VDI 2004/1)*. As in the USA, which promotes environmental research projects in nanotechnology through the Environmental Protection Agency (EPA), there are applications of nanotechnology in the environmental technology field (Trück 2004 in the "Nanotechnology, Materials, Production (NMP)" programme) of the 6th Framework Research Programme of the European Union.

The European Commission is pursuing the goal of strengthening scientific excellence in Europe with the 7th Framework Research Programme (FRP). The annual budget is to be significantly increased to 10,000 million Euros. More than 4,500 million Euros annually is intended for thematic priorities including the "technology initiatives". Nanotechnologies, materials and sustainable development are one of the thematic priorities in the 7th FRP. According to the current timetable, the first calls can be expected at the end of 2006[7].

6 Hullmann (2001) investigated international technology transfer using nanotechnology in a study. Various indicators such as the number of publications, patents etc. were included for this.

7 Additional current information about the 7th European Commission Framework Research Programme is available at www.cordis.lu/era/fp7.htm

Research and development in Germany on the industrial side is currently concentrated in the raw material and chemical sectors *(Harper 2002)*. Industrial stakeholders in nanotechnology are mainly represented by large companies such as BASF, Degussa, Henkel or Siemens *(see Reitberger in Venture-Capital 2002, Hullmann 2001, own research)* and small startup companies. These have often been hived off from the university and non-university research area; there is often an intensive exchange of knowledge and staff between startup companies and universities. Medium-sized enterprises have been less involved in nanoresearch to date. Networks of stakeholders such as the BMBF competence centres, the Fraunhofer Nanotechnology Association or other research associations aim to make it possible particularly for small and medium-sized enterprises to enter nanotechnology. Business networks such as Materials Valley e.V for material-based technologies, MST-Netzwerk Rhein-Main for microsystem technology and Optence e.V for optical technologies are providing Hessian companies with an excellent platform for networking and for know-how transfer. The research programmes and market for nanotechnology are shown in detail on pages 42 to 47.

1.6 Technology impact assessment

Possible risks and impacts of nanotechnology are being analysed and assessed

The analysis and assessment of possible risks and negative impacts of nanotechnology on humans and the environment are occupying a major place in public discussion and scientific research. The escorting Innovation and Technology Analyses (ITA) on nanotechnology conducted by the Federal Ministry for Education and Research (BMBF), backed up by toxicological investigations, have indicated possible risks arising out of the use of nanotechnology – at the same time, they drew attention to the opportunities which it opens up. However, a general assessment of nanotechnology is not yet possible. Instead, the specific possible applications of nanotechnology must and will be examined in relation to their specific uses and the consequent limiting factors. The great opportunity, as opposed other new technologies such as genetic engineering, lies in the fact that estimates of the technological impacts can already be successfully included in the analyses at very early stages of development. This subject is described in more detail on page 48.

2 Application potential and application areas for nanotechnology in environmental technology

2.1 Tasks and application areas of environmental technology

The field of environment protection and renewable energies is considered to be one of the most important sectors of the future. With approximately 3.8 per cent of the German labour force, there are more people employed in this area than in mechanical engineering, vehicle manufacturing or the food trade. With more than 70,000 employees in more than 2,000 companies concerned with environmental and energy technology, Hessen is among the leaders in Germany.

The objectives of environmental technology are air, water and soil protection, resource saving, and the avoidance of environmental problems

The objectives of environmental technology in practice are air, water and soil protection, resource saving, and the avoidance of environmental problems. In the past, actions have usually been driven by existing environmental problems; the matter was identified starting from an environment problem, e. g. the eutrophication of watercourses. Possible options and solutions based on this were determined. This understanding of environmental technology can be described as conventional environmental technology.

The media-related, cure-oriented view of environmental technology has given way to a preventive and holistic approach

Thus it is important not only to recognise and eliminate environmental pollution, or to avoid or minimise harmful environmental impacts, for example by filter systems – but also to avoid and prevent them in the first place. An example of this is the debate about production and product integrated environmental protection.

Environmental technology is a cross-sector technology which uses disciplines such as process technology, biology or chemistry

Environmental technology is also a cross-sector technology which uses the most diverse basic technologies and disciplines such as process technology, biology or chemistry. Technical solutions are integrated in systems which support an ecological and economically efficient solution to environmental problems or prevent these occurring. These are based on innovations in basic technologies such as materials technology, process technology, biotechnology, microtechnology and information technology, and at the same time on key technologies such as nanotechnology (Angerer et al. 1998). Together with the basis technologies as drivers, the environmental protection objectives have also repeatedly sparked off innovations in environmental technology. New regulations have resulted in further developments, or new developments, in materials or processes. Company philosophies oriented towards the primary objectives of sustainability have resulted in new, ecologically compatible products.

An example of innovations in nanotechnology achieved by the setting of environment targets is provided by the research projects at the USA Environment Protection Agency for the reduction of arsenic in drinking water. The aim of these projects is to meet the legally prescribed limit value of ten microgrammes of arsenic per litre of drinking water using nanotechnology-based filter systems *(see e. g. Trogler 2002).*

Figure 9: Fixed bed reactor system made of iron hydroxide pellets - Bayoxide® E33 – with very finely structured surfaces in the nanorange for arsenic adsorption (*Source: Bayer AG, Severn Trents Services*)

The basic environmental technology fields in Hessen are shown in Table 1. They are classified both by environmental compartments and by specific product applications. (Possible application areas of nanotechnology are also shown to give a better overview; these are described in detail in the following chapters).

Table 1: Fields covered by environmental technology in Hessen, specific product applications, and possible uses of nanotechnology

Water / Wastewater

- Application examples
  Water treatment and wastewater treatment systems, sewage technology and clarifier technology
- Possible application areas of nanotechnology
  Filtration, membrane technology (colloid membrane), absorption / adsorption, ion exchanger, functionalised surface layer, filler, selective catalytic converters / catalysis, sensitive pollutant detection

Waste / Recycling

- Application examples
  Recycling, waste treatment and waste disposal, flue gas cleaning, landfill technology
- Possible application areas of nanotechnology
  Sensitive pollutant detection, filtration, heat resistant wall panelling

Energy / Clean Air / Climate Protection

- Application examples
  Solar energy, wind energy, biomass, fuel cell technology
- Possible application areas of nanotechnology
  Dye sensitised solar cells, organic solar cells, fuel cell (mobile hydrogen storage, separation of hydrogen, oxygen and water, catalytic fuel conversion and implementation), miniaturised battery systems, compact zeolite reactors

Integrated Product Policy IPP

- **Application examples**
  Production technology, material selection, increased efficiency
- **Possible application areas of nanotechnology**
  Specific material design, new types of alloys / materials, lighter carrier and structure components, precise machining process, quality control at the atomic scale, switchable material properties, environment friendly properties such as "non-contaminating", new types of adhesive technologies, self-organisation processes

Analytics / Measuring, Control and Regulation Technology

- **Application examples**
  Water and wastewater management, analytics, process monitoring and control
- **Possible application areas of nanotechnology**
  Lab-on-chip sensor systems, combined sensors / actuators

To date there has been little information allowing estimations of the future development of individual environmental technologies and application areas. An essential impetus for the development of the environmental technology market, particularly in water and wastewater treatment and water pollution monitoring systems, is provided by environmental legislation[8]. Competitive features in this largely saturated market in Germany are product diversification and the cost factor.

The most urgent challenges for global environment protection are resource protection and the water and energy supply

From a global point of view, the most urgent challenges for future environment protection are the protection of resources, and the question of water and energy supplies *(European Commission 2004/2)*. Thus, worldwide initiatives were launched at the United Nations world summit meeting for sustainable development in Johannesburg in 1992 which are also being energetically pursued by the European Union in the context of the action plan for environmental technology.

As part of the campaign against poverty, the **Water Initiative** has set out to provide clean drinking water and develop clarifier systems with the support of technologies and processes developed in the EU. According to a market analysis by Frost & Sullivan, seawater desalination alone for the global market is forecast to have an average annual growth rate of about ten per cent by 2010, by which time the worldwide market is expected to be worth approximately 2,400 million US$. The largest market shares are anticipated in the Gulf countries, Saudi Arabia and Southern Europe *(Frost & Sullivan 2004/4)*.

The market volume in the EU for water pollution monitoring systems in 2005 is estimated at more than 420 million US$ *(Frost & Sullivan 1999)*. Technology trends in this market are precise and long-term reliable operating systems.

8 An overview of future expected or changing EU, Germany and Hessen legal environmental requirements is provided by "Innovation radar environmental law" (see www.hessen-umwelttech.de). This hessen-umwelttech action line project shows the future market opportunities for environmental technology providers, resulting from the new regulations.

It is anticipated that the market for water treatment systems in Germany will continue to grow annually by two per cent until 2010. Accordingly, the market value in Germany for the year 2010 is estimated at more than 115 million US$. Membrane technology, with more than half the turnover, will dominate the market *(Frost & Sullivan 2004/2)*.

Through the **Energy Initiative** it is proposed to achieve higher energy efficiency in developing countries by more intelligent use of fossil fuels and traditional biomass, and by increased use of renewable energy sources. It will be task of a **Renewable Energies** coalition to specify objectives and timeframes for increasing the proportion of renewable energy sources in the overall energy mix, thus creating a significant need for environmental technology. Basic current environmental problems such as the greenhouse effect and air pollution are associated with the energy supply issue.

The rapid growth of portable wireless devices such as laptops, mobile telephones, etc. is a basic impetus for energy supply and storage systems. For example, lithium technology forms an important application area of nanotechnology. Here, carbon nano tubes are incorporated in the electrode *(Frost & Sullivan 2004/1)*. Another area is the development of micro fuel cells. Central components for these, such as the membrane, are also based on nanotechnology. The direct methanol fuel cell will have a major opportunity in this area. The first prototypes of laptops, mobile telephones, cameras or PDAs fitted with a fuel cell already exist *(see Rastogi 2004)*. Average market growth rates of more than 200 per cent over the next five years are forecast for the global market of micro fuel cells for portable devices *(Frost & Sullivan 2004/3)* – however, the market is starting at a very low level.

In addition to direct use in energy systems, nanotechnology is also of interest in areas where its use can reduce energy consumption. An example of this is the white LEDs based on nanotechnology. Due to their high efficiency not only can energy costs be reduced, but CO_2 emissions can be halved as well. The possible energy saving by the use of White LEDs in Germany corresponds theoretically to the energy output of two nuclear power stations. They are approximately ten times more efficient than conventional light bulbs. Their market value in Germany alone is estimated at 500 million Euros. Annual sales growth of ten to fifteen per cent is forecast for innovative products in this area *(Bachmann 2004)*.

A survey among environmental technology suppliers in Hessen showed that there are discernible short and medium term trends in fuel cell development and that hydrogen technology will play an important role in the long term. It was also established that the market for renewable energies is growing. It is assumed that there will be an increase in demand for biodegradable products, which means that impulses for innovation can be expected from biochemistry *(M-Result 2002)*.

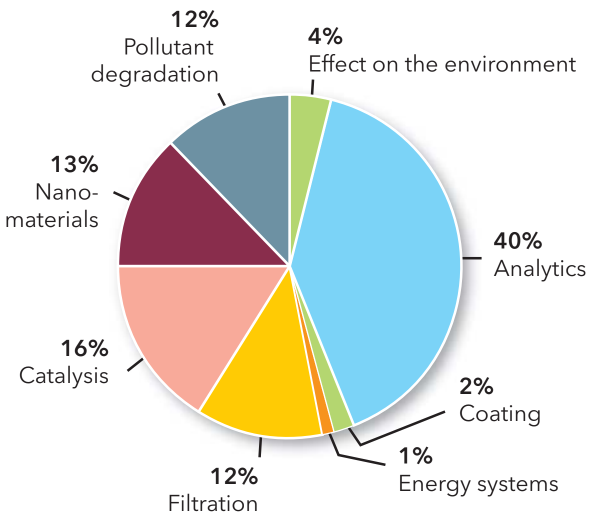
2.2 Application potentials of nanotechnology in environmental technology

Nanotechnology can enable new technologies or help to save inputs or energy

Nanotechnology has considerable potential for solving problems related to the future challenges of scarce raw materials and the provision of clean drinking water or efficient products and processes. This is shown by analyses of the literature and by discussions with experts. Nanotechnology can act as an "enabler" of new technologies in the field of environmental technology or indirectly support environmental protection, e. g. by savings in inputs or energy. Furthermore, environmental technology can be used to evaluate and master the effects of nanotechnology. This may concern issues of labour safety or analysis.

The first concrete application areas of nanotechnology for environmental technology firms have been identified both from replies given by consultant experts and from the literature. It has been indicated that nanostructured materials have already been used in environmental technology applications for some time (e. g. metal nanoparticles in catalytic converters and particle filters for exhaust gas reduction (CO, NOx, hydrocarbons, carbon black particles), but materials for new applications are also being developed (solar technology, lab-on-chip systems). Environmental technology has often been called an "indirect" application area, i. e. environmental technology firms can profit from innovations which have been developed for other sectors or application areas. Known implementation focuses of nanotechnology in environment protection can therefore be found in the areas of energy, easy-to-clean surfaces, membranes and analytics. On the other hand, there is still a great deal of potential in the conventional environmental technology fields for concrete and economically interesting nanotechnology applications, for example in emissions reduction or decontamination. The first membranes based on nanotechnology exist in the filtration field (for example Nanoweb® from Hollingsworth & Vose). The nanotechnology focus on some application areas of environmental technology mentioned above are also confirmed by an analysis of the project promotion of the American EPA National Center for Environmental Research *(Figure 10)*[9].

Figure 10: Project promotion of the US EPA for nanotechnology and environmental technology according to the environmental technology classification (own research)



The possible uses of nanotechnology in environmental technology based on the technology areas water / wastewater and waste, energy / clean air / climate protection, analysis / measurement and control technology, and integrated product policy are shown below *(see Table 1, pages 20/21)*.

9 Search for research projects on http://es.epa.gov/ncer/index.html (date 9. 9. 2004)

Technology area: Water / Wastewater

Catalytic and separation processes, i. e. chemical process technology, are used in the water / wastewater technology area and in purification processes. The use of nanotechnology in membrane technology, catalytic surfaces, ion exchangers or electrode separation processes in the purification and treatment of water, air and earth contamination has been demonstrated in scientific work. The possible uses in the area of filtration, catalysis or pollutant decomposition are shown in detail in Chapter 2.4.

Technology area: Waste / Recycling

Purification and separation processes for water / wastewater also play an important role in the waste / recycling area, e. g. for purification of process water in production or landfill wastewater.

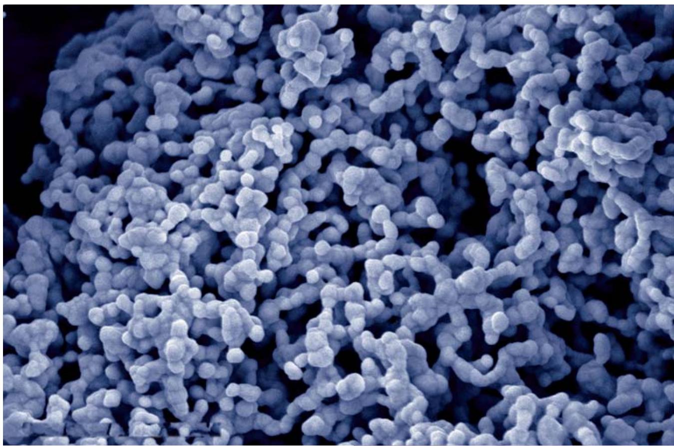
At present, there are no known examples or scenarios for specific applications in the waste technology area. However, there are a number of interesting possibilities, such as adhesive bonding which can be disbonded when required, or new approaches for production processes using nanotechnology to manufacture multifunctional materials more cost-effectively and with lower resource consumption and waste. And finally, a large contribution to management with less waste and energy consumption is expected from the visions of self-assembly (bottom-up, *see Figure 5, page 9*), where the atoms arrange themselves to form structures – in much the same way as ice or salt crystals *(Royal Society 2004)*.

Nanotechnology opens up other potentials, for example in easy-to-clean surfaces, which can make a contribution to resource savings and wastewater reduction.

Technology area: Energy, Clean Air, Climate Protection

Solar energy, wind energy or fuel cell energy belong to the area of energy, clean air and climate protection. Technologies for mobile hydrogen storage, for separation of hydrogen, oxygen and water in the fuel cell, for catalytic fuel conversion and combustion in the fuel cell and technologies in solar cell and battery development are already being worked on. All of these contain nanotechnology materials. A new type of solar cell using nanotechnology is being researched with dye sensitised solar cells and organic solar cells allowing new possible designs and applications *(Hinsch 2004)*. The Gratzel cell, a cost-effective solar cell, is also based on nanotechnology (TiO_2 nanoparticles, with dye molecules adhering to their surface, are used as base material). There is a glass electrode on the top of the cell through which sunlight reaches the inside of the cell. The intermediate space is filled with an electrolyte.

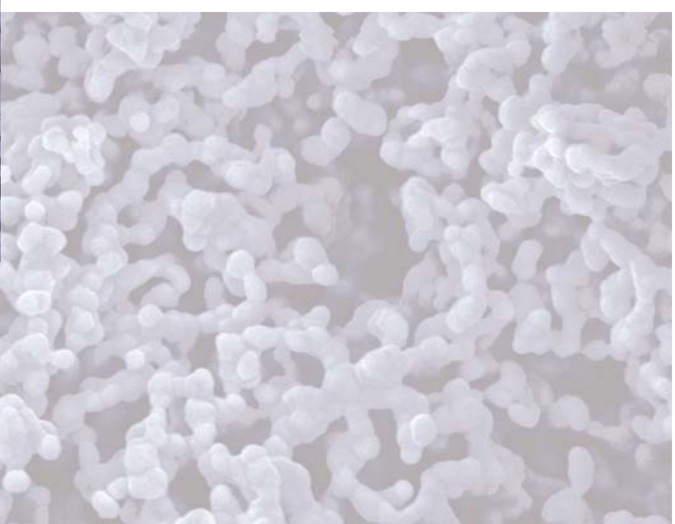
Figure 11: Nanosilver may be incorporated in various materials and protects against bacteria (*Source: Fraunhofer IFAM*)



Technology area: Integrated Product Policy (IPP)

Integrated Product Policy is concerned with actions and technologies which improve the environmental friendliness of products. It covers, for example, the energy supply, the selection of materials, the production process, resource consumption in the manufacturing and usage phases, and environmentally friendly dismantling. Studies by *Steinfeldt et al. (2004)* on the sustainability effects of nanotechnology products show that very large ecological efficiency potential can be realised by using coatings based on nanotechnology. The use of nanotube catalytic converters in styrene synthesis achieves an energy saving potential of just under 50 per cent at the styrene synthesis process stage, thus demonstrating the importance of nanotechnology for efficient resource management *(Steinfeldt et al. 2004)*.

Surfaces with environmentally safe properties are interesting: possibilities here include surfaces with non-contaminating and self-cleaning effects *(see Figure 1, page 6)*, or with insulation properties and protection mechanisms, e. g. against IR / UV radiation or corrosion. The first products for surface treatments (glass, wood), such as cleaning agents, varnish and paint for the domestic user, are already on the market. In the materials area, new switchable materials – research is being carried out, for example, on switchable wetting behaviour – and adhesive bondings are conceivable which are also useful for the environment.



Technology area: Analysis, Measuring / Controlling / Regulation Technology (MCR)

Miniaturised sensors based on nanotechnology as well as simple onsite analytics with remote telemetric query systems and onsite disposition (e. g. in a borehole) are conceivable for the area of environmental analytics. The work for this is in the research and prototyping stages. The possible uses in the analytics field are shown in detail in Chapter 2.4.

Evaluation of the functionalities and the technology areas

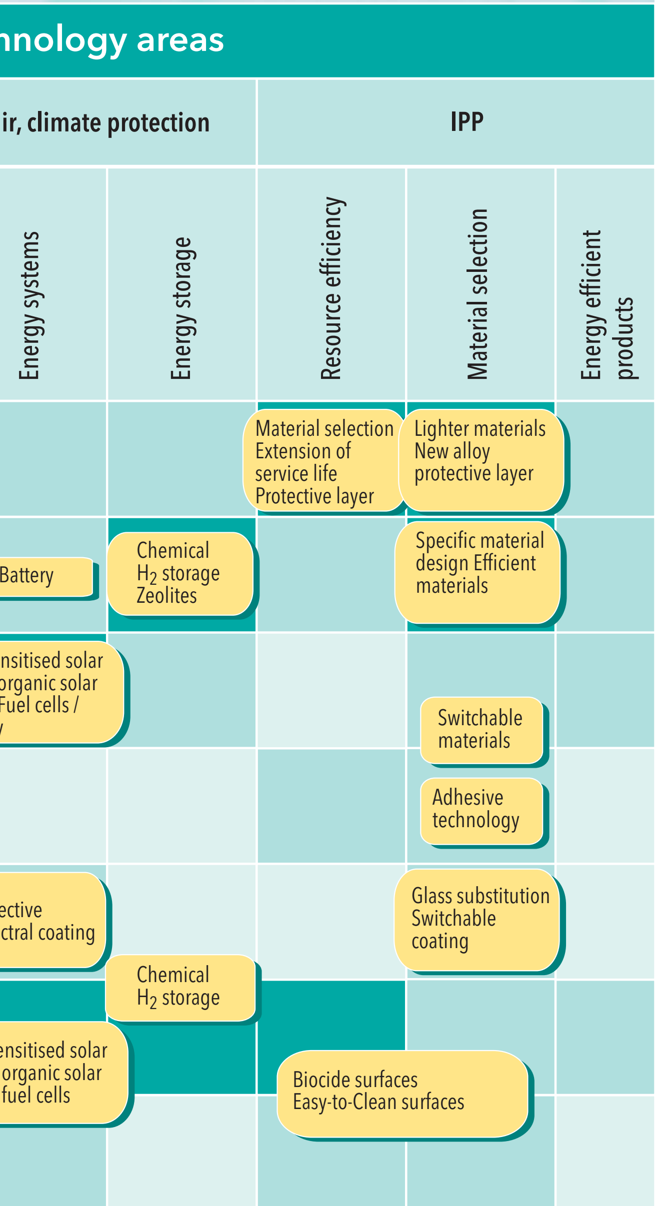
In Table 2 on the following page, the application potentials of nanofunctionalities *(see Explanations on page 14)* are compared qualitatively to environmental technology fields and assessed. The assessment is subjective and is concerned with identifying potential areas in which future applications appear expedient or possible as far as we can know at present. The authors have presented a "snapshot" based on analyses of the literature and replies received from experts.

- Large application area obvious
- Application area conceivable
- Application area still not clear

		Improved properties with regard to	Environmental tech					
			Water / wastewater	Waste		MCR	Energy, clean a	
			Purification / treatment	Avoidance	Handling	Monitoring / Analysis	Air cleaning, cleaning	
Nanotechnologie	Mechanical functionality	Hardness, tribological properties, break resistance, toughness, super plasticity			Anticorrosion mechanically stable wall lining			
	Special geometric features	Atomic precision, large surface / capacity ratio	Catalytic converter Ion exchanger Filter systems Fillers			Reactive surface	Filter / Catalytic converter	
	Electrical functionality	Discrete energy levels, customised electrical properties				Lab-on-Chip nanosensors / nanoactuators		Dye se cells / c cells / I Battery
	Magnetic functionality	Magnetic properties (superparamagnetism)						
	Optical functionality	Colour, fluorescence, transparency				Optical measuring systems		Sel spe
	Chemical functionality	Reactivity, selectivity, surface wetting, functional groups	(Photo)catalysis surface coating adsorption / absorption	Catalysis surface property		Nanochemical sensors Lab-on-Chip	Catalytic converters	Dye se cells / cells /
	Biological functionality	Analyses biosystems, bio construction plans for nanosystems	Bioreactors catalysis		Bioreactors catalysis	Nanobiosensors Bio-Lab-on-Chip	Biofilter	

Table 2 shows potential application areas of nanotechnology in environmental technology as a type of application map. Environmental technology companies can see which nanotechnology functionalities support and optimise processes and products in their field. Nanoresearchers can identify which of their functionalities can be used in environmental technology.

Table 2: Application map for nanotechnology functionalities in environmental technology



2.3 Comparison of the application areas with the sector structure of environmental technology companies in Hessen

Hessen is represented today in all important environmental technology fields. Companies in this sector in Hessen make an annual turnover of 12,400 million Euros. Figure 12 shows the turnover of Hessian environmental technology companies broken down by technology fields for the year 2001 *(M-Result 2002)*. The heading "Other" includes integrated environmental technology, resource saving product development, and the planning and construction of environmentally friendly production systems and processes. The illustration shows that many environmental companies in Hessen are particularly active in the area of water / wastewater. This field is also a major application area for nanotechnology.

The chemical, biological and geometric as well as – to a lesser degree – mechanical and electrical functionalities *(see Table 2)* have a large innovation potential for environmental technology. In comparison, there is a particularly large selection of companies in Hessen in the technology areas of water / wastewater, waste / recycling, and energy / clean air / climate protection *(see also Table 1 and Figure 12)*. This shows that Hessen has a particularly large innovation potential in the field of water and wastewater with regard to the use of nanotechnology in environmental technology. Individual applications from these fields such as filtration, pollutant decomposition or catalysis are shown in detail in Chapter 2.4.

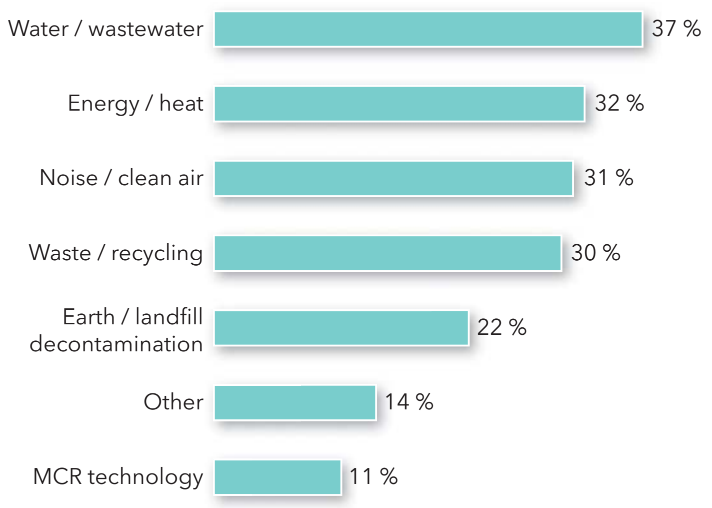


Figure 12: Proportion of companies per technology area excluding sector of "Environmental management / law / Eco-Audit" and "Nature protection / ecology" (Total > 100 % as multiple classification is possible, *M-Result 2002*)

Hessen is represented in the nano competence centres by a number of companies engaged in the sectors of nanotechnology relevant to environmental technology. Hessen is well represented in the competence centres for nanoanalytics, functionality through chemistry, and nanomaterials. Hessen is particularly strongly represented in the chemical industry area, which serves to drive the nanoresearch application area: With the companies Aventis Research & Technologies (now partly Sanofi Aventis Group), Degussa AG, Creavis GmbH and Merck Patent GmbH, four Hessen companies from the chemistry sector are among the top 20 nanopatent applicants *(FEH 2004)*.

The sectors of nanomaterials, nanochemistry, nanoelectronics and nanoanalytics are particularly well covered in the area of university research: Research is being carried out on functional materials and materials by the Technische Universität Darmstadt, the Johann Wolfgang Goethe University in Frankfurt, the Justus-Liebig University in Gießen, and the Kassel University. Nanochemistry is a focus of the Justus-Liebig University in Gießen and the Philipps-Universität in Marburg. Nanosensors are being researched at the Darmstadt, Gießen, Kassel and Marburg universities, and at the Gießen-Friedberg and Wiesbaden technical colleges. The research competence is considered to be 'good' to 'very good'. The new initiative for networking the nanoresearch universities in the NanoNetzwerkHessen[10] was introduced in March 2004 *(see page 50)*. The competence networks in Hessen are also listed on page 50.

In addition, the DECHEMA – society for chemical technology and biotechnology – has been established as an intermediary between research and industry. Its role is to participate in the development of chemical technologies and processes and to work on new findings from research and development for practical use.

The transfer of knowledge and technical know-how between scientific institutions and particularly the small and medium-sized enterprises (SME) from industry and commerce is promoted by the TechnologieTransferNetzwerk-Hessen (TTN-Hessen). The primary objective is to make the available technology in Hessen transparent and to link the stakeholders. It is intended that the access to innovative technologies and scientific findings should be made easier particularly for small and medium-sized enterprises, e. g. by supporting the search for suitable partners for the respective research and development tasks. In addition, the university and research experts will be offered the opportunity to present their technological know-how in the virtual technology and competence market.

10 See www.nanonetzwerkhessen.de

2.4 Possible applications of nanotechnology in environmental technology

The possible applications of nanotechnology in environmental technology are shown below under selected application headings. This presentation makes no claims to completeness. The application areas can be assigned to one or more environmental technology fields in Hessen *(see Table 1, pages 20 / 21 and Table 2, pages 26 / 27)*.

Application area: Filtration (filters, membranes)

Technology area: water / wastewater, clean air, integrated product policy

Nano-optimised membranes / filters are used to remove unwanted substances from water or air much more efficiently than with conventional filter systems. Such filters offer a precisely adjustable pore size, and at the same they can take on extended functions, e.g. as an active surface membrane. Membranes based on nanotechnology can also have a catalytic effect through incorporation of reactive centres (metal oxides) or through immobilisation of bio catalytic converters *(see Catalytic pollutant decomposition application area, page 31)*. New materials such as carbon nanotubes expand the field of membrane components. General application areas are wastewater purification, the treatment of laboratory and drinking water, the separation of viruses, bacteria, pigments or ultra-small particles from air and water, and side-product separation in chemical processes. The **technological bases** are formed by inorganic structures such as nanoporous zeolite and customised polymer membranes with sintered nanoparticles or nanopores in the filtration.

Application examples are:

- filter membranes made of deformable ceramics with nanoparticles,
- carbon nanofibre membranes or CNTs for filtration,
- microporous thin film based on inorganic, crystalline materials such as zeolite or porous silicon
- supported polymer membranes, the pores of which are filled with a functional polymer or oligomer liquid,
- membranes made of organic plastic as nanofabric (pore diameter and membrane fibres are in the nm range), or
- catalytic membranes for separating water into hydrogen and oxygen.

The **advantage** of nanotechnology in filtration is that it can provide customised membranes offering very much more efficient permeability, selectivity, reactivity and low contamination due to closely spread pore sizes, high porosity, high specific surface and nanostructured asymmetry. The interaction of the membranes occurs not only on their outside surface but through the complete volume of the material.

Figure 13:
Picture of a Nanoweb® "nanofilter" (*Source: Hollingsworth & Vose*)

Practical example of a membrane: nanofibre coating for filter materials

The development of filter materials with a new type of architecture has been worked on in cooperative research between the Philipps-University Marburg (Prof. Dr. Andreas Greiner, Prof. Dr. Joachim H.Wendorff) and the filter manufacturer Hollingsworth & Vose – with financial support from the Federal Ministry of Education and Research (BMBF). The technological base is a nanofabric made of fibres revealing an average diameter of 200 nanometers or smaller. The "Nanoweb®" filter, the development of which emerged from the collaboration, is based on a thin layer of fibres on a carrier material. The nanofibre lattice determines the filter fineness. The advantage of this filter medium is a small overall pressure loss with simultaneous high intake capacity of the separated particles. Filter replacement intervals are increased and the energy required to flow through the filter is significantly reduced. The plastic nanofibres are manufactured using the electrospin process. The filter can be used for different filtering purposes; the market value is estimated at several hundred million Euros.

The first products have already found an application. Ion bombardment and etching, self-organisation of the electron spinning or molecular imprinting are used as manufacturing methods for nanotechnological membranes.

Literature: EPA (2002), Masciangioli, Zhang (2003), Siegel et al. (1999), TAB (2004)

Application area: pollutant retention

Technology areas: water / wastewater, waste, clean air, integrated product policy

Nanoparticles and nanostructured surfaces can be used in exhaust air cleaning and water purification to retain pollutants by absorption, adsorption and immobilisation in exhaust air cleaning and water purification. The **technological base** is formed by fixed-bed nano-matrices from carbon, zeolites or a membrane with high selectivity, surface and sorption capacity.

Application examples are:

- dendritic nanoscale chelating agents for retention of metal ions such as Cu(II) ions from industrial wastewaters (e. g. ultra-filtration) or for reduction of chlorinated alkenes such as perchlorethylene (PCE), or
- molecular sieve material made of porous, activated nanocarbon (Carbon Nano Tubes) as a sorption agent for dioxins or for gas separation.

Amongst other things, a **significant benefit** is the high sorption energy, particularly of Carbon Nano Tubes (it is almost three times higher than that of activated charcoal). Other possible uses are seen in the immobilisation of heavy metals or radionuclides. However, large-scale applications in the near future are restricted by low availability and high costs.

The first products are already available on the market (nanoscale fixed bed matrix for arsenic reduction); a number of materials are currently being researched.

Literature: EPA (2002), TAB(2004), Bachmann (1998), Masciangioli und Zhang (2003)

Application area: Catalytic Pollutant Decomposition

Technology areas: water / wastewater, clean air, integrated product policy

Catalytic processes can decompose pollutants using oxidation and reduction. Nanoparticles and nanostructured surfaces can be used here for example in exhaust air and wastewater catalysis technology, soil and polluted site decontamination, odour breakdown, and in fuel cells or in combustion processes (petrol engine). The catalytic converters are partly activated by light (photocatalysis). The **technical bases and application examples** are:

- catalytic converters with gold nanoparticles as an odour filter,
- catalytically effective nanoparticles in (ceramic) films of fuel cells or for increased efficiency in fuel combustion,
- formation of catalytically effective nano metal oxide particles by using the protein structure of ferritin for the reduction of chromium-VI to insoluble chromium-III in the groundwater,
- nanoparticles of various oxidation and reduction agents (titanium dioxide, zinc oxide, iron hydroxide pellet or bimetals such as iron / palladium, iron / silver or zinc/palladium, etc.) can stimulate pollutant breakdown and microbial growth. Zinc oxide nanoparticles can be used as photocatalysts for the treatment of chlorinated phenols and simultaneously as sensors,
- direct injection of nanoscale iron particles in the subsoil for breaking down chlorinated organic compounds such as trichloroethylene.

Practical example of pollutant decomposition: Sunlight replaces chlorine in the swimming pool

An innovative swimming pool coating for cleaning the pool water (JUSTadd-WATER® technology) is about to be launched on the market. It was developed as a result of collaboration between the Technische Universität Darmstadt (Dr. Thomas Mayer, material and geoscience faculty, specialist area – surface research) and Böhme Schwimmbadtechnik (Mario Böhme). This resource-saving technology is based on the cleaning effects of nature and protects the environment by dispensing with the chemicals needed, e. g. chlorine, for water sterilisation in the established oxidation methods. The technological base is a microscopically thin functional layer which is distributed evenly over the surface of the swimming pool. The layer consists of a special chemical compound based on nanotechnology which uses two natural cleaning processes: Firstly, all kinds of bacteria and algae are killed directly on the swimming pool wall with electrons stimulated by light. Adhering dirt is broken down into its chemical structure by the photocatalytic reaction, rinsed out by the water and washed away by the water movement in the swimming pool. Secondly, the layer uses light to form active oxygen and hydroxyl radicals which evenly distribute themselves in the water volume of the swimming pool and thus also serve to sterilise the pool water.

The **benefits** and uses of the implementation of nanotechnology can be seen in the production of highly selective catalysts for pollutant decomposition and the process industry:

- improvement in efficiency of available technologies such as in-situ pollutant decomposition, ultra-filtration,
- pollutant decomposition in chemical reactions or in biological pollutant decomposition without undesired side-products through high reactivity of nanoparticles resulting from their crystal form and lattice arrangement,
- nanoscale particles can be removed more effectively from the desired contamination location, and
- significant resource savings by using customised catalysts in the process industry which increase the reaction yield and reduce the reaction energy.

It is true that the use of nanotechnology for manufacturing catalysts is not new, but more targeted and rapid development started only a few years ago with increasing technical progress in basic research. The applications are still partially in the pilot stage. Therefore, the essential challenges for the future will doubtless be in an acceleration of basic research and an increased implementation and use of this basic cross-sector technology.

Literature: Bachmann (1998), Masciangioli und Zhang (2003), TAB (2004)

Application area: nanosensors (Lab-On-Chip systems)

Technology areas: analytics, measurement, control and regulation technology

Environmental analytics are concerned with analysing substances or substance mixtures and their composition or determining their physical properties such as solubility, steam pressure, melting point, boiling point, and flash point.

Nanobased sensors can be used for detection, analysis and in-situ monitoring; they can also be partly used simultaneously as catalysts (see application area: catalytic pollutant decomposition). **Technological bases are formed by reaction, adsorption or bonding processes in sensors for use in optical, biological, chemical or physical analysis.**

Chemical sensors consist of a receptor (made, for example, of metals, semi-conductors or polymers) which interacts with the substances to be analysed. These are converted into electrical impulses by a transducer and forwarded. The following **application examples** of chemical sensors based on nanotechnology are known:

- conductometric, nanocrystalline metal oxide sensors or semi-conductive single-wall CNT as conductometric gas sensors for detection of nitrogen dioxide or ammonia,
- palladium nanowire as conductometric hydrogen sensor,
- sensors – adsorbent, chemically functionalised, or coated with nanoporous zeolite film – with nano strain gauge, or
- molecularly imprinted polymers (nanopores) or surfaces (self-organised monolayer).

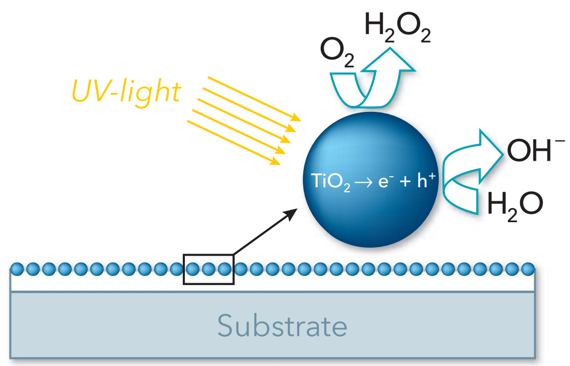


Figure 14: New functionality through nanotechnology: Photocatalysis with TiO_2-nanoparticles (*Source: NANO-X*)

Chemical sensors based on biosensors are functionalised with biomolecules or complete cells and enable a selective connection of biomolecules, viruses or cells using molecular recognition.

Lab-on-Chip systems are based on:

- switchable molecular membranes (nanofluidic) based on lipids in ultra-thin layers,
- self-organising monolayers for biomolecule or cell immobilisation, or
- coated semiconductor quantum points (connection semiconductors, polymers) as fluorescence markers.

The **benefits** and uses are molecule-specific lab-on-chip systems, faster and more selective detection, miniaturised analysis systems, the use of larger and more molecule-selective surfaces on chip systems, direct "on-site" analysis results, large analysis areas (cells, molecules, metal bondings), in some cases significantly increased sensitivity, approach speed and selectivity, and a low energy consumption.

The challenges are to master the critical dimensions and to reach long-term thermal and chemical stability of the material. There are still partial problems in the coupling to electrical or optically readable structures. The development and manufacture require a high degree of interdisciplinarity between the chip industry, biochemistry and engineering.

A number of sensors are already in use. Most of the concepts, e. g. the development of more practical chemical sensors based on molecularly imprinted polymers, are still at the research stage.

Practical example of nanosensors: Chemical sensors with substance-selective nanolayer

In the context of a research project promoted by the Federal Ministry for Education and Research (BMBF), Thomas Recording GmbH in Gießen in cooperation with partners at the Gießen, Freiburg, Bochum and Southampton (UK) universities has developed the world's first multi-channel chemical sensor which can detect, among other things, transmitters such as dopamine. This development has been possible due to the use of special multi-channel fibres. These fibres have to seven metal wires isolated from each other, although the complete multifibre has a diameter of only 100 microns. Metal contact surfaces at the tip of the fibre are covered with a thin sensor layer of a few nm. Specially for use in plant research, Thomas Recording GmbH has succeeded for the first time in manufacturing thin electrodes of a few nm with which it is possible to perform physiological measurements in the intercellular spaces of a leaf.

Literature: EPA (2002), TAB (2004), Royal Society and Royal Academy of Engineering (2003), Roco und Tornellini (2002)

3 Innovation potential and technology transfer approaches

As a cross-sector technology, nanotechnology has a large innovation potential for many technical applications in the field of environmental protection. The use of nanotechnology can result in more efficient, more selective or miniaturised solutions. It can contribute directly to resource efficiency and indirectly to the improvement and further development of environmental technology applications. Thus, a coupling of both technologies can contribute to further strengthening of Hessen's scientific and economical position in the fields of environmental technology and nanotechnology.

Nanotechnology is particularly interesting for Hessen's environmental technology enterprises if …

Nanotechnology provides a multitude of functionalites for environmental technology *(see Table 2, pages 26 / 27)*. Whether the use of nanotechnology will be of advantage for environmental technology companies – for their products or processes – depends on the answers to a number of central questions. Thus, nanotechnology is particularly interesting for Hessen's environmental technology companies

- if **physical-chemical processes** play an important part or a particularly large surface / volume ratio considerably influences the process,
- if **biological processes** have considerable importance for the products, especially the interface between biological and technical components,
- if the **design and functionalisation of surfaces or boundary surfaces** have considerable importance and their influence increases the usefulness of the product,
- if **miniaturisation** is to be further developed or compact systems (e. g. sensors and energy supply) are necessary, or
- if nanotechnology is **relevant as an additional competitive factor**.

First questions, how nanotechnology can be used in one's own products or to create new business areas

To decide whether or how nanotechnology can find use in a company's own products and process or for creating new business areas, the following points should be checked *(Classification according to Bullinger 1994)*:

Can nanotechnology replace a technology used up to now? (technology substitution)

An environmental technology company will have to determine whether nanotechnology can or will replace known or established technologies which is uses at present, and thus improve the state of technology, or whether future nanotechnology innovations will replace one's own product.

Possible examples
Nanostructured surfaces for adsorption and fillers in catalytic reactors replace existing adsorption media; fuel cells replace batteries as a new source of energy for portable wireless electrical equipment; biocide and / or photocatalytic surface coatings for swimming pools replace water treatment systems; metal hydride storage as chemical hydrogen storage replaces physical pressure tanks.

Is nanotechnology complementary to the technologies used up to now? (complementary technology)

An environmental technology company will have to determine whether nanotechnology can improve its processes or products for environmental protection and thus increase the product's usefulness, or whether nanotechnological innovations will improve other products and processes or a new business area will emerge.

Possible examples
New sensor systems made possible by more efficient energy supplies from smaller battery systems or micro fuel cells; easy-to-clean surfaces, or lotus effect, resulting in resource-saving processes for the process industry; efficiency of solar cells enhanced by non-contaminating surfaces.

Does nanotechnology give rise to a new field of technology?

An environmental technology company will have to determine whether possible innovative applications with as yet unknown functionalities and application areas can be produced by nanotechnology. It is important here for technical competence to be backed up by knowledge of the market and of customer requirements, i. e. the combination of technology-push and market-pull creates new products.

Possible examples
Artificial emulation of photosynthesis; new application areas for low-cost sensitised dye or organic solar cells in the consumer goods market or as solar paint; pipeline systems with integrated cleaning functionality; integration of organic solar cell and sensor systems based on organic electronics.

At the same time, this structuring of nanotechnology research and development makes it easier to select an application area in environmental technology and to identify suitable collaborations or partnerships.

The examples *(see Chapter 2.4)* show the innovative potential of nanotechnology for environmental technology products and processes. From the scientific point of view, there are still a number of unanswered questions concerning long-term behaviour and effects across the life cycle, or the potential toxic properties of some nanotechnology materials *(see Chapter 1.6)*. Considerations of this kind should be taken realistically into account by companies at an early stage, because social non-acceptance of nanotechnology – whether justified or not – blocks research and development in this key technology field.

The possible applications of nanotechnology described here are largely based on use in established markets which either show low growth or are saturated. Market shares are increased by ousting other competitors, which means that the use of nanotechnology must assert itself against established technologies or processes. Differentiation, technology leadership and system integration are starting points or part of the strategy for environmental technology companies in Hessen to survive in competition with nanotechnology or to develop new areas:

Differentiation, technology leadership and system integration are starting points for business strategy

- **Price differentiation**
  The use of nanotechnology in environmental technology clearly results in more cost-effective and more efficient products and processes (e. g. low-cost solar cells with improved efficiency). Usage costs must be compared with manufacturing costs. Easy-to-clean surfaces save cleaning costs or result in more efficient system operation, e. g. the coating of solar cells.

- **Technology leadership differentiation**
  The use of nanotechnology in environmental technology (e. g. self-sufficient measurement sensors for pollutants with high precision or highly selective membranes) enhances a technology qualitatively, or fills a market niche. Small and medium-sized enterprises (SME) will become "technology enablers" for nanotechnology and thus assume a pioneering role.

- **System integration by system providers**
  As nanoresearch requires high expenditure and qualified staff, horizontal or vertical cooperations in the value chain are useful and necessary. In turn, such cooperations may emerge on the market as system providers and thus also follow the general trend in environmental technology. In this way, the integration ability among environmental technology companies is particularly remarkable, as they often integrate other technologies in their products and services and provide them as systems with concrete customer benefits. Cooperation or operator models can form new business bases, offering Hessen's SMEs the chance to participate in nanotechnology as part of the value chain.

Knowledge transfer and exchange among the various disciplines drive the application forward

Knowledge transfer and exchange among the various disciplines are also an impetus for the use of nanotechnology in environmental technology. To date, the contact points between opportunity-driven and research-driven nanotechnology and the problem-oriented approach of environmental technology are still missing. Environmental technology companies are often unaware of the spectrum provided by nanotechnology or where its application areas are. Conversely it is also the case that nanotechnology businesses and research institutions are unaware of the environmental technology problem areas and challenges.

The gaps between technology-push and market-pull must be closed

The objective and starting point for Hessian environmental technology companies – particularly in the fields: "water / wastewater", "energy", "clean air", "measuring and control technology" and for integrated policy issues – is therefore to close the gap between technology-push and market-pull.

Basic starting points for technology transfer

The promotion of technology and information transfer between environmental technology and nanotechnology should already be effected in both disciplines in the early phases of research. Basic research should take the possibilities for subsequent marketing more into account than it has done up to now. Vertical and horizontal cooperation in the value chain must therefore be pursued in order to combine product development and practice, and in particular to integrate SMEs in the development process.

Various possibilities are available here for companies in Hessen. This can take place in virtual form by setting up "Communities" or establishing businesses in a value chain, or by research and development cooperation in a specific technology park or industrial estate.

Materials Valley e.V.[11], a competence network for material research and material technology in the Rhein Main region, is a good example of how important impulse effects can be achieved by a thematic cluster of competences and contribute to the image of a technology and the region. A link-up between nanoscientists has been initiated in Hessen with the recently established "NanoNetzwerkHessen[12]" network.

The "hessen-nanotech" and "hessen-umweltech"[13] action lines of the Hessian Ministry of Economics support the research and development of environmental technology and nanotechnology products and services – e. g. by competence atlases, information brochures, events and projects – and make Hessen's competencies better known both inside and outside the region.

The HA Hessen Agentur GmbH[14] manages these action lines and is the contact partner for nanotechnological companies and environment technology businesses which are interested in nanotechnology for improving their products or processes. It advises on promotional and location issues and guides interested parties to the responsible technology transfer points between university and business – in collaboration with the technology transfer network (TTN-Hessen)[15] – and to European partners. The Hessen Agentur GmbH publishes competence atlases for individual technologies in order to provide an overview of the separate business and research activities in Hessen.

Against the background of the study of environmental technology providers in Hessen *(M-Result 2002)*, the following strategies of Hessen environmental technology companies are also important for nanotechnology transfer.

- **Research:** Key drivers of the environmental technology market in the past were legislation and promotional programmes. The extensive German and European research programmes provide opportunities for promoting technology research and project consortia.
- **Collaboration:** The importance of joint research and development projects has been low up to now. This contrasts with the particular research intensity and interdisciplinarity of nanotechnology, which means that businesses must develop cooperation and networks to incorporate know-how in their own research and development.

11 http://materials-valley-rheinmain.de
12 www.nanonetzwerkhessen.de
13 www.hessen-nanotech.de and www.hessen-umwelttech.de
14 www.hessen-agentur.de
15 www.ttn-hessen.de

- **Differentiation:** The strategy of smaller companies is market differentiation with an innovative product. Nanotechnology can be an approach here for using the available nanotechnology research competences in Hessen for joint environmental technology innovations.

A further opportunity to manage cooperation in research and development is offered by research programmes aimed at technical implementation of available research results and the promotion of mature products. In this way, entry to nanotechnology for companies is made possible via research and development cooperation with universities and nanotechnology startup businesses.

To ensure the subsequent transfer of results, industry should increasingly make its requirement profiles available to researchers and institutions. Networking with research and industry must be further expanded if expert knowledge is to be more effectively used and integrated in the future. The "hessen-nanotech" and "hessen-umwelttech" action lines support companies and research institutions here by making contacts with research and development.

However, it is also clear that nanotechnology – like all branches of science – is an international research field. The networks are linked world wide. Accordingly, the exchange of information and participation in research projects takes place internationally. However, at the regional level, the boundary conditions for the establishment of technology businesses can be decisively influenced in order to achieve or maintain international technical market leadership.

Literature

In the author's opinion, the literature printed in bold type is recommended for an in-depth analysis or wide comprehensive overview of nanotechnology.

Altmann, Stephan (2004)
Chemical Nanotechnology for Sustainability, lecture by Dr. Stephan M. Altmann, BASF Polymer Research / Polymer Physics, BASF Ludwigshafen, at the "Nano meets environmental technology" symposium on July 02, 2004 at the Fraunhofer IAO in Stuttgart
Download at www.bum.iao.fraunhofer.de/nano

Angerer, Gerhard; Bierhals, Rainer; Hipp, Christiane; Kalb, Henry; Lang, Jürgen; Marscheider-Weidemann, Frank; Nathani, Carsten; Reger, Guido; Schön, Michael (1998)
IInnovationspotenziale von Umwelttechnologien: Innovationsstrategien im Spannungsfeld von Technologie, Ökonomie und Ökologie, published by the German Umweltbundesamt, Physika-Verlag, Heidelberg 1998

Bachmann, Gerd (1998)
Innovationsschub aus dem Nanokosmos – Technologieanalyse, Bericht des VDI-Technologiezentrum, Abteilung Zukünftige Technologie des Vereins Deutscher Ingenieure (VDI), Düsseldorf 1998

Bachmann, Gerd (2003/1)
Deutschland ist stark in den Nanowissenschaften, aber teils noch schwach in der Umsetzung, in: VentureCapital Magazin Sonderausgabe: Nano- / Mikrotechnologie – Märkte und Visionen, 4. Jahrgang, November 2003, Verlag GoingPublic Media AG,Wolfratshausen 2003

Bachmann, Gerd (2004)
Nanotechnologie – Kleine Dimensionen und großes Potential für die Umwelttechnik? Lecture by Dr. Gerd Bachmann, VDI-Technologiezentrum GmbH Düsseldorf, Abt. ZT-Consulting at the "Nano meets environmental technology" symposium on July 02, at the Fraunhofer IAO in Stuttgart
Download at www.bum.iao.fraunhofer.de/nano

Bachmann, Gerd; Rieke, Volker (2004)
Nanotechnologie erobert Märkte – Deutsche Zukunftsoffensive für Nanotechnologie, published by the Ministry of Education and Research (BMBF), Berlin 2004, available on www.bmbf.de

Bierhals, Rainer (2000)
Mikrosystemtechnik – wann kommt der Marktdurchbruch? Miniaturisierungsstrategien im Technologiewettbewerb zwischen USA, Japan und Deutschland, Physica-Verlag, Heidelberg 2000.

BMBF (2002)
Nanotechnologie in Deutschland – Standortbestimmung, Studie des Bundesministerium für Bildung und Forschung (Hrsg.), Referat Öffentlichkeitsarbeit, Bonn 2002

Bullinger, Hans-Jörg (1994)
Einführung in das Technologiemanagement: Modelle, Methoden, Praxisbeispiele, Teubner Verlag, Stuttgart 1994

Colvin, Vicki (2003)
Wie gefährlich ist Nanotechnologie – über Nutzen und Chancen von Nanomaterialien, in: MIT'S Magazine of Innovation – Technology Review (German Edition), Nr. 1, Mai 2003, Heise Zeitschriften Verlag, Hannover 2003

Drexler, Eric; Peterson, Chris (1991)
Unbounding the Future: the Nanotechnology Revolution, New York 1991

EPA (2002)
Nanotechnology and the Environment: Applications and Implications STAR Progress Review Workshop, August 28-29, 2002, Arlington, VA, U.S. National Center for Environmental Research.
Download at www.nano.gov/html/res/workshops.html

Europäische Kommission (2003)
Breaking down barriers to technologies to protect the environment and boost competitiveness, European Commission, Environmental Technology Consultation, DG Environment, Environmental Technology Action Plan Announcement 242, IP/03/430, Brussels 2003

Europäische Kommission (2004/1)
Auf dem Weg zu einer europäischen Strategie für Nanotechnologie (KOM(2004) 338 endgültig), Communication of the Commission of the European Union, Brussels 2004

Europäische Kommission (2004/2)
Stimulation von Technologien für nachhaltige Entwicklung: Ein Aktionsplan für Umwelttechnologie in der Europäischen Union (KOM(2004) 38 endgültig), Communication of the Commission of the European Union an den Rat und das Europäische Parlament, Brussels 2004

Farkas, Robert et al (2004)
Nanotechnologie pro Gesundheit: Chancen und Risiken (Innovations- und Technikanalyse), Bericht im Auftrag des Bundesministeriums für Bildung und Forschung durch Aachener Gesellschaft für Innovation und Technologietransfer AGIT mbH (Aachen), Aachener Kompetenzzentrum Medizintechnik (Aachen), Fraunhofer Institut für Lasertechnik e.V. (ILT) (Aachen), Fraunhofer Institut für Molekularbiologie und Angewandte Oekologie e.V. (IME) (Aachen) und IGES Institut für Gesundheits- und Sozialforschung GmbH (Berlin), Aachen 2004
Download at
www.bmbf.de/pub/nano_pro_gesundheit_bericht.pdf

Feder, Barnaby (2003)
As uses grow, tiny materials' safety is hard to pin down, New York Times of 03/11/2003, New York 2003

FEH (2004)
Materialbasierte Technologien in Hessen: eine Bestandsaufnahme, Studie der Forschungs- und Entwicklungsgesellschaft Hessen mbH (FEH), Wiesbaden, FEH-Report Nr. 665, Wiesbaden 2004

Frost & Sullivan (1999)
European Water Pollution Monitoring Markets, Report Nr. 3785-15, Frost & Sullivan Ltd, London 1999

Frost & Sullivan (2004/1)
Advanced Energy Storage Technologies, Report Nr. D289, Frost & Sullivan, Texas / USA 2004

Frost & Sullivan (2004/2)
European Municipal Water and Wastewater Treatment Equipment Markets, Report Nr. B391-15, Frost & Sullivan Ltd, London 2004

Frost & Sullivan (2004/3)
World Micro Fuel Cell Markets For Portable Devices – Consumer, Industrial and Military, Report Nr. A659-27, Frost & Sullivan, 2004

Frost & Sullivan (2004/4)
The Desalination Plant Markets in Europe, The Middle East & North Africa, Report Nr. B317-15, Frost & Sullivan Ltd, London 2004

Greenpeace (2003)
Future Technologies, Today's Choices: Nanotechnology, Artificial Intelligence and Robotics – A technical, political and institutional map of emerging technologies, by Alexander Huw Arnall, University of London, London 2003

HA (2005)
Nanotechnologie in Hessen – Eine Bestandsaufnahme auf Basis von Unternehmensbefragungen, Study by HA Hessen Agentur GmbH (formerly FEH), Wiesbaden 2005

Harper, Tim (2002)
The emerging cutting-edge Technology – Nanotechnology international, in: VentureCapital Magazin Sonderausgabe: Nanotechnologie – Märkte und Visionen, 3. Jahrgang, November 2002, Verlag GoingPublic Media AG, Wolfratshausen 2002

Hinsch, Andreas (2004)
Neue Potentiale in der Solarenergieforschung durch Nanotechnologie, lecture by Dr. Andreas Hinsch, Fraunhofer ISE, Freiburg, at the "Nano meets environmental technology" symposium on July 02, 2004 at the Fraunhofer IAO in Stuttgart
Download at www.bum.iao.fraunhofer.de/nano

Hullmann, Angela (2001)
Internationaler Wissenstransfer und technischer Wandel – Bedeutung, Einflussfaktoren und Ausblick auf technologische Implikationen am Beispiel der Nanotechnologie in Deutschland, Physika-Verlag, Heidelberg 2001

Masciangioli, Tina; Zhang, Wei-Xian (2003)
Environmental Technologies at the Nanoscale, Environmental Science & Technology, March 1, 2003
Download at www.nano.gov/html/res/GC_ENV_PaperZhang_03-0304.pdf

M-Result (2002)
Umwelttechnologieanbieter in Hessen: eine Bestandsaufnahme, Study by M-Result GmbH, Mainz, December 2002

NNI (2002)
Small Wonders, Endless Frontiers – A Review of the National Nanotechnology Initiative (NNI, National Nanotechnology Initiative der USA), Committee for the Review of the National Nanotechnology Initiative, National Research Council, Washington 2002
Download www.nano.gov/html/res/smallwonder.html

Rastogi, A. K. (2004)
Anwendung von Mikro- und Nanostrukturen in der Wasserstoff- und Brennstoffzellentechnologie – A short stuy report no. BT 70046-01 for the "hessenumwelttech" action line of the Hessian Ministry of Economics, Transport, Urban and Regional Development, Wiesbaden 2004

Roco, Mihail; Tomellini, Renzo (2002)
Nanotechnology – Revolutionary opportunities and societial implications, 3rd Joint EC-NSF Workshop on Nanotechnology, 31 January / 01 February 2002 in Lecce, European Commission, Research Directorate-General, Luxembourg 2002

Royal Society and Royal Academy of Engineering (2003)
Nanotechnology: views of Scientists and Engineers – Report of a workshop of the Nanotechnology study, June 2003, Royal Society (www.royalsoc.ac.uk) and the Royal Academy of Engineering (www.raeng.org.uk)

Royal Society and Royal Academy of Engineering (2004)
Nanoscience and nanotechnologies: opportunities and uncertainties, Study of the Royal Society and the Royal Academy of Engineering, London, 2004 (www.raeng.org.uk)

Siegel, Richard; Hu, Evelyn; Roco, Mihail (1999)
Nanostructure Science and Technology – AWorldwide Study, by National Science and Technology Council (NSTC), The Interagency Working Group on Nano-Science, Engineering and Technology (IWGN), December 1999, Maryland 1999
Download at http://itri.loyola.edu/nano/final/

Steinfeldt, Michael (2003)
Mit Nanotechnologie zur Nachhaltigkeit, Schriftenreihe des IÖW 166/03, Berlin 2003

Steinfeldt, Michael; von Gleich, Arnim; Petschow, Ulrich; Haum, Rüdiger; Chudoba, Thomas; Haubold, Stephan (2004)
Nachhaltigkeitseffekte durch Herstellung und Anwendung nanotechnologischer Produkte, Schriftenreihe des IÖW 177/04, Berlin 2004

TAB (2004)
Nanotechnologie, Bericht des Ausschusses für Bildung, Forschung und Technikfolgenabschätzung des Deutschen Bundestages, March 2004, Deutscher Bundestag Drucksache 15/2713. Download at http://dip.bundestag.de/btd/15/027/1502713.pdf
Published as work report no. 92, July 2003

Trogler, William (2002)
Nanostructured Porous Silicon and Luminescent Polysiloles as Chemical Sensors for Carcinogenic Chromium(VI) and Arsenic(V), Proceeding des EPA Nanotechnology and the Environment: Applications and Implications STAR Progress Review Workshop, August 28-29, 2002, Arlington, Virginia / USA

Trück, Beate (2004)
Nano meets Umwelttechnik – Förderprogramme der EU, lecture by Dr. Beate Trück, Büro Brüssel der Fraunhofer-Gesellschaft, at the "Nano meets environmental technology" symposium on July 02, 2004 at the Fraunhofer IAO in Stuttgart
Download at www.bum.iao.fraunhofer.de/nano

VDI (2004/1)
Präsentationsmaterial „Reise in den Nanokosmos" des VDI Technologiezentrum GmbH, Zukünftige Technologien Consulting, Download at www.nanotruck.net/pdf/nanoTruck_Broschuere.pdf

VDI (2004/2)
Nanotechnologie als wirtschaftlicher Wachstumsmarkt – Innovations- und Technikanalyse, Zukünftige Technologien Nr. 53, Bearbeitung durch Wolfgang Luther, Norbert Malanowski, Gerd Bachmann, Andreas Hoffknecht, Dirk Holtmannspötter, Axel Zweck, Zukünftige Technologien Consulting der VDI Technologiezentrum GmbH, Düsseldorf 2004

VentureCapital Magazin (2002)
VentureCapital Magazin Sonderausgabe: Nanotechnologie – Märkte und Visionen, 3. Jahrgang, November 2002, Verlag GoingPublic Media AG,Wolfratshausen 2002

Werner, Matthias (2004)
Nanotechnologie und Nanomaterialien – Applikationen und Marktpotenzial, lecture by Dr. Matthias Werner, NMTC, Berlin, at the "Nano meets environmental technology" symposium on July 02, 2004 at the Fraunhofer IAO in Stuttgart
Download at www.bum.iao.fraunhofer.de/nano

Zhang, Wei-Xian (2003)
Nanoscale iron particles for environmental remediation: An overview, in: Roco, Mihail C. (Hrsg.): Journal of Nanoparticle Research 5: 323-332, 2003, Kluwer Academic Publishers, Arlington (VA) 2003

Research programmes and the market

Nanoresearch, particularly basic materials research, is largely financed out of public research funds. Many countries have set up their own research programmes. The USA spent a total of 1,857 million US $ for nanotechnology research and development over the period from 1997 to 2003, and approximately 770 million US $ in 2003. In the same period, 1,281 million US $ was invested in research and development in Western Europe, an increase of 500 per cent compared to 1997 (Greenpeace 2003). Figure 15 shows an international comparison of the expenditure on nanotechnology promotion in 2004.

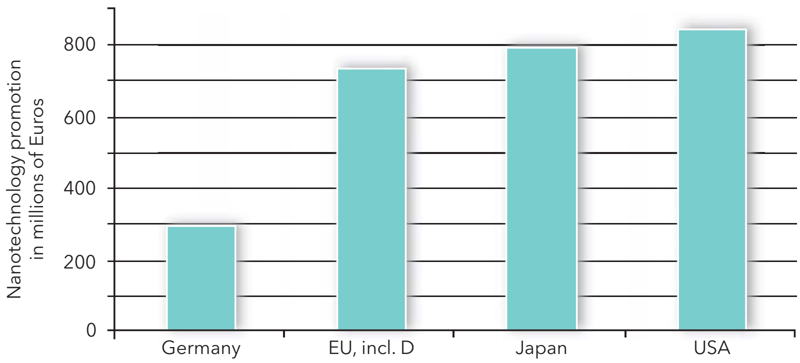


Figure 15: International comparison of nanotechnology promotion (VDI 2004/1)[16]

right:
Table 3: International and national research programmes with respect to nanotechnology and relevance to the environmental protection (own research)

USA

National Nanotechnology Initiative (NNI), www.nano.gov

Budget: 2002: 600 million US $
2003: 770 million US $
2004: 849 million US $
2005: 982 million US $

21st Century Nanotechnology Development Act

Budget: 2005 to 2008:
just under 3,700 million US $

Elements of research project related to environmental technology:

- Nanotechnology in environmental protection
- Possible effects of nanotechnology on the environment and society

EU

Nanoforum, www.nanoforum.org

Budget: 6th Framework Programme 2002 to 2006: 1,300 million Euros

7th Framework Programme 2007 to 2013: 2,600 million Euros

Elements of research project related to environmental technology:

- New eco-efficient production processes
- Conversion / treatment of production waste

16 Total for Germany: Project promotion plus BMBF institutional promotion and project promotion by the Federal Ministry of Economics and Labour (BMWA)

D

Nanonet, www.nanonet.de

Budget: 2002: 88.5 million Euros
2003: 112 million Euros

Elements of research project related to environmental technology:

- Assessment of technology impacts, risks
- Sustainability and nanotechnology (Steinfeldt 2003)
- Ecological implications of the promotional activities

D

BMBF Framework programme WING – Werkstoffinnovationen für Industrie und Gesellschaft (Material innovations for industry and society)

Budget: 2004 to 2006: 250 million Euros

Elements of research project related to environmental technology:

- Resources and energy efficient production
- Batteries / hydrogen storage using nanostructures
- Ecological implications of surface treatment
- New materials for product innovations

D

BMBF Framework programme "Nanotechnologie erobert Märkte" (Nanotechnology conquers markets): NanoMobile, NanoLux, Nano for Life, NanoFab, NanoChance

Budget: 2004: 250 million Euros

Nanoresearch in the USA

In the USA, the central research and development programmes and activities in the nanotechnology subject area are bundled in the National Nanotechnology Initiative (NNI) *(NNI 2002)*. 982 million US $ were invested in 2005 for nanotechnology research from the USA budget. The long-term commitment of the USA has recently been assured for the period 2005-2008 by the "21st Century Nanotechnology Development Act" which provides almost 3,700 million US $ for the five research organisations: NSF, DoE, NASA, NIST and EPA *(European Commission 2004/1)*. Figure 10 *(page 23)* illustrates the distribution of the promotional measures of the EPA according to environmental technology classifications.

Whereas R&D nanotechnology programmes in the USA are co-ordinated or centralised, in the European research landscape there seems to be a gap between various rapidly advancing programmes and the financial sources *(European Commission 2004/1)*.

Nanoresearch projects at the National Center For Environmental Research of the U.S. Environmental Protection Agency (EPA)

(Selection, date September 9, 2004, see http://es.epa.gov/ncer/index.html)

Application area: Analytics

A Life Cycle Analysis Approach for Evaluating Future Nanotechnology Applications
Carnegie Mellon University, period: 05/2003 – 04/2005

Advanced Nanosensors for Continuous Monitoring of Heavy Metals
SUNY at Binghamton, New Mexico State University
period: 05/2003 – 04/2006

Compound Specific Imprinted Nanospheres for Optical Sensing
Clarkson University, University of New Hampshire – Main Campus, period: 06/2003 – 05/2006

In-Situ Measurement of Vehicle Exhaust Emissions Using Supramolecular Conducting Polymer Films
Fractal Systems Inc., period: 10/2002 – 07/2003

Low Cost Organic Gas Sensors on Plastic for Distributed Environmental Monitoring
University of California – Berkeley,
period: 05/2003 – 04/2006

Multi-Analyte Nanoelectronic Air Pollutant Sensors
Nanomix Inc., period: 03/2004 – 08/2004

Nanomaterial-Based Microchip Assays For Continuous Environmental Monitoring
New Mexico State University, period: 06/2003 – 05/2006

Nanostructured Porous Silicon and Luminescent Polysiloles as Chemical Sensors for Carcinogenic Chromium(VI) and Arsenic(V)
University of California – San Diego
period : 01/2002 – 12/2004

Use of fullerenes as groundwater pollution tracers
University of Arizona, period: 01/1996 – 10/1999

Application area: Analytics / Pollutant Decomposition

Simultaneous Environmental Monitoring and Purification Through Smart Particles
University of Florida, period: 02/2002 – 02/2005

Application area: Coating

Biomimetic Nanostructured Coating for Dry Machining
NanoMech LLC, period: 03/2004 – 08/2004

Application area: Filtration

Development of High Surface Area Material and Filter Media
eSpin Technologies Inc., period: 04/2002 – 09/2002

Nanocomposite-Based Filter for Arsenic Removal in Drinking Water
Materials Modification Inc., period: 10/2002 – 07/2003

Use of Ozonation in Combination with Nano-crystalline Ceramic Membranes for Controlling Disinfection By-products
Michigan State University, period: 05/2003 – 05/2006

Application area: Filtration / Analytics

Microbial Removal and Integrity Monitoring of High-Pressure Membranes Used For Water Treatment
University of Illinois at Urbana, period: 01/1997 – 01/1999

Application area: Catalysis

Engineering of Nanocrystal Based Catalytic Materials for Hydroprocessing of Halogenated Organics
University of Texas at Austin, period: 09/2000 – 08/2004

Enhanced VOC Oxidation
Compact Membrane Systems Inc.
period : 04/2002 – 09/2002

Plasmon Sensitized TiO_2 Nanoparticles as a Novel Photocatalyst for Solar Applications
Clemson University, period: 07/2002 – 06/2005

Removal and Disposal of Perchlorate From Drinking Water by Novel Capacitive Deionization
Material Methods LLC, Zeitraum: 03/2004 – 08/2004

Application area: Catalysis / Decontamination

Dendritic Nanoscale Chelating Agents: Synthesis, Characterization, Molecular Modeling and Environmental Applications
Howard University, California Institute of Technology, University of Michigan, period: 12/2002 – 12/2004

Application area: Decontamination

Developing Functional Fe(0)-based Nanoparticles for In Situ Degradation of DNAPL Chlorinated Organic Solvents
Carnegie Mellon University, period: 05/2003 – 04/2006

Nanoscale Bimetallic Particles for In Situ Remediation
Lehigh University, period: 01/2002 – 12/2004

Application area: Environmental Effects

Green Engineering of Dispersed Nanoparticles: Measuring and Modeling Nanoparticle Forces
Pennsylvania State University – Main Campus
period : 02/2002 – 01/2004

Implications of Nanomaterials Manufacture and Use: Development of a Methodology for Screening Sustainability
BRIDGES to Sustainability, Rice University
period: 05/2003 – 04/2005

Nanoresearch in the EU

In the 6th Framework Programme of the European Union, approximately 1,300 million Euros, 7.5 per cent of the research funding applied for, is reserved for the primary subject areas of nanotechnology research and nanosciences, knowledge-based multifunctional materials, new production processes and equipment. Altogether, 3,420 millionEuros will be provided for projects in the "Industrial Technologies" and "Materials" areas. Environmentally friendly technologies, which also include applications of nanotechnology, play a central part here *(European Commission 2003)*.

Apart from long-term interdisciplinary research to expand the present state of knowledge, the 6th Framework Programme focuses principally on engineering for the development of materials and components, the development of measurement and control equipment and instruments, and applications in areas such as medicine, chemistry, optics, energy technology and environmental technology *(VDI 2004/1)*.

With respect to the next framework programme, the European Commission specified a harmonised innovation policy at the European level and criticised the unfavourable working conditions for innovations in a communication of May 12, 2004 and others. Against this background, the European Commission proposed the following strategy:[17]

- planned doubling of the budget for nanotechnologies / new materials for the 7th Framework Research Programme (to run from 2007 to 2013) (budget to date in the 6th Framework Programme: 1,300 million Euros),
- transnational collaboration of research institutions,
- high-tech centres for peak research infrastructure and interdisciplinary researcher training,
- better coordination of national EU research policies,
- favourable working conditions for technology transfer and innovation: transfer of research excellence in products and processes,
- promotion of public acceptance for nanotechnology, and
- inclusion of the environmental, health and safety aspects in nanotechnology research.

Nanoresearch in Germany

The Federal Ministry of Education and Research (BMBF) has been promoting nanotechnology since the early 1990s in the framework of the "Material Research" and "Physical Technologies" programmes and "Laser Research" and "Optoelectronics". In the last six years, the BMBF has promoted joint nanotechnology projects with a total of 340 million Euros. Thus the expenditure has continually increased.

At the initiative of the BMBF, eight nano competence centres have been established since 1998 with the aim of improving research networking and promoting collaborations[18]. The tasks of the competence centres include public relations, education and further training, the creation of an economically attractive milieu and advising interested parties, mainly from industry, on the respective nanotechnology field. The BMBF favours an initial coordination of R&D activities and projects, together with advice for applicants on the centres. Table 4 shows the thematic focus points and total nanotechnology promotion funding by the BMBF for the period 2002 to 2005 *(Bachmann and Rieke 2004)*.

17 Statement at: www.cordis.lu/nanotechnology/src/communication.htm

18 See at: www.kompetenznetze.de

Subject area	Focus points	Grant 2002	2003	2004	2005
Nanomaterials	Nanoanalytics, Nanobiotechnology, Nanostructure materials, Nanochemistry, CCN, Nano competition, Nanochance	**19.2**	**20.3**	**32.7**	**38.1**
Production technologies	Ultra-thin layers, ultra-precise surfaces	**0.2**	**0.8**	**2.2**	**2.2**
Optical technologies	Nanooptics, Ultra-precision machining, Microscopy, Photonic crystals, Molecular electronics, Diode laser, OLED	**18.5**	**25.2**	**26.0**	**26.0**
Microsystem technology	System integration, Nanosensors, Nanoactors, Energy systems	**7.0**	**7.0**	**9.4**	**10.2**
Communication technologies	Quantum structure systems, Photonic crystals	**4.3**	**4.0**	**3.6**	**3.4**
Nanoelectronics	EUVL, Lithography, Mask technology, eBiochips, Magnetoelectronics, SiGe-Bectronics	**19.9**	**25.0**	**44.7**	**46.2**
Nanobiotechnology	Manipulation techniques, Functionalised nanoparticles, Biochips	**4.6**	**5.4**	**5.0**	**3.1**
Innovation and technology analysis	ITA studies	**0.2**	**0.5**	**0.2**	–
Total for all subject areas (in millions of Euros)		**73.9**	**88.2**	**123.8**	**129.2**

Table 4: Thematic focus points and nano promotion grant from the BMBF from 2002 to 2005, in millions of Euros (*Bachmann und Rieke 2004*)

Finally, mainstream innovations have been identified by the BMBF and a future research programme with 250 million Euros has been put in place for the reinforcement of nano competence in Germany. The following focus points are promoted:

- **NanoFab**: ultra-precise high throughput manufacture for nanoelectronics,
- **NanoLux**: efficient radiation sources for innovative light applications,
- **NanoMobil**: nanomaterials and nanotechnologies in the car, and
- **Nano for Life**: nanomaterials and nanobiotechnology for life sciences and health.
- **NanoChem** will be the focus point in the framework programme "Material innovations for industry and society – WING": Chemical nanotechnologies are promoted for new materials and products.

A search for research projects in Germany with clear reference to nanotechnology and applications in environmental technology produced no results. However, there are research projects, e. g. verification methods or filter systems based on nanotechnology which could also be used in environmental technology.

Nanoresearch by industry

The industry research and development activities concentrate mainly on base materials and chemistry – German companies have traditionally been strongly represented in this area *(Harper 2002)*. This is confirmed by an assessment of patents *(see Reitberger in VentureCapital 2002, Hullmann 2001, own research)*: A large part of the business is represented by large established concerns such as BASF, Degussa, Henkel or Siemens which have their own research departments and use spin-offs to enter the market with new competences and technologies. There are also spin-offs as start-ups at the universities and cooperations between large enterprises and the universities with a view to benefiting jointly from their from knowledge and infrastructure *(cf. die Degussa Projekthäuser[19])* On the other hand, small and medium-sized enterprises (SME) are still not a driving force in the research and development of nanotechnology systems. The reasons for this are the high investment costs for personnel and infrastructure and insufficient cooperation among companies. However, due to the special requirements which nanotechnology places on interdisciplinarity, it will not be long before SMEs complete cooperation agreements with divided competencies.

An important contribution is made in Germany by numerous small and medium-sized nano enterprises which were founded as start-ups and focus on specialised development. Their business areas are more oriented to manufacturing, analysis and equipment technologies while the large enterprises are more interested in system solutions with large turnovers *(Bachmann 2003/1)*.

Market

Information about estimating markets, market sizes, the patent situation and time periods for commercialisation is extremely limited. Application and market perspectives of nanotechnology for products and product groups have been analysed and evaluated in a current study by the VDI: "Future Technologies Consulting for the BMBF". There was a particular focus on the market potential in selected lead markets: chemicals, automotive construction, optics, medicine / life sciences, and electronics. Indicators of the market potential have also been derived from patent data. In addition, information on the implementation of nanotechnology in German companies was acquired and evaluated in a survey *(VDI 2004/2)*. This showed that the chemicals area, including materials, clearly occupies the top position among nanotechnology companies in Germany. The central functional characteristics are definitely conventional and application-specific, such as improved material properties and surface functionalisation *(Werner 2004)*. According to a study by Business Communications Company Inc. (BCC), a tenfold increase compared with the present day is anticipated in the period 2005-2010 for the area of nanofiltration and membranes *(in Royal Society 2004)*. BCC gives a market volume of 70,000 million US$ over the next 20 years for seawater desalination using nanofiltration techniques *(in TAB 2004)*.

However, it is anticipated that nanotechnology will affect almost all sectors *(Werner 2004)*. Among the European states, Germany has certainly the best qualifications for successful activity in the nanotechnology field in the medium and long term *(Werner 2004)*.

19 See: www.creavis.com/site_creavis/de/default.cfm?content=projecthouses/mission

Technology impact assessment

The technology impacts which can be associated with nanotechnology have been, and are continuing to be, analysed and evaluated. In addition to the companies which carry out testing of any of their products which contain nanotechnology, the BMBF has commissioned a study of "Nanotechnology and sustainability" *(BMBF 2002, Steinfeldt 2003, Steinfeldt et al. 2004)* and of "Nanotechnology for health – opportunities and risks" as an escorting measure for the promotion of nanotechnology. The latter publication analyses medical applications and health effects of nanotechnologies in diagnosis, therapy and prevention, taking account of possible side effects (Farkas et al. 2004). The American EPA has initiated a four million US$ programme to examine the environmental effects of nanotechnology. However, this contrasts with approx. 849 million US$ made available for nanotechnology research and development in 2004 *(Feder 2003)*. As shown in Table 4 (page 46), an average of just under 0.3 per cent of the nanotechnology project promotion budget was spent on technology analysis in Germany in the 2002–2005 grant period.

The office for evaluating technology impact in the German Bundestag (lower house of the German Parliament) reveals in its final report, "Nanotechnology status and perspectives", that the state of research for potential environmental and health effects during the manufacture and application of nanotechnology processes and products is still unsatisfactory. Insufficient knowledge could serve to hinder the introduction of nanotechnology on the market, because society could take this "insufficient knowledge" as a reason for general non-acceptance of nanotechnology *(TAB 2004)*.

Attention is currently being focused on the effects of nanoparticles on human health. Investigations are being carried out into their dispersion and their effects on human organs, e.g., for example overcoming the blood-brain barrier or possible effects on cell functions. At the moment it cannot be stated generally whether nanoparticles are either dangerous or harmless *(Colvin 2003)*. No analyses of possible impacts arising out of the use and disposal of nanotechnology products have been made, and no account has been taken of integrated product policy (IPP) aspects. The USA Environmental Protection is known to have conducted a research project on the application of life cycle analyses in nanotechnology (*Royal Society 2004*). There is also to some extent a lack of information on positive and negative long-term effects and product behaviour in connection with a number of potential applications of nanotechnology. The absence of standards also makes an evaluation difficult.

A differential consideration of the various application fields is necessary for the further development and consideration of possible opportunities and risks. Generalised assessments can hardly be made in view of the diversity of nanotechnology; instead, potential opportunities and risks should be evaluated in individual tests early and objectively against the concrete application background. For example the DECHEMA / VCI working group, "Responsible Production and Use of Nanomaterials"[20], sets out to identify opportunities and possible risks of chemical nanotechnology and to advance successful economic and technical implementation by initiating appropriate actions with reference to ethical, ecological, social and economic aspects.

20 See: www.dechema.de/NANOSAFETY.html

Information & Addresses

Contact persons for nanotechnology and/or environmental technology advice in Hessen

Action line hessen-umwelttech

- Competence presentation nationally and internationally
- Information dissemination for reinforcement of competences
- Networking technologies
- Technology marketing
- Grant and location advice and project consultancy

Contact:

www.hessen-umwelttech.de

HA Hessen Agentur GmbH
Alfred Stein
Project manager hessen-umwelttech
Abraham-Lincoln-Straße 38-42
D-65189 Wiesbaden
Telephone +49 (0) 611 / 774-8648
Fax +49 (0) 611 / 774-8620
alfred.stein@hessen-agentur.de

Hessisches Ministerium für Wirtschaft,
Verkehr und Landesentwicklung
Maria Rieping
Kaiser-Friedrich-Ring 75
D-65185 Wiesbaden
Telephone +49 (0) 611 / 815-2472
Fax +49 (0) 611 / 815-2228
maria.rieping@hmwvl.hessen.de

Action line hessen-nanotech

- Competence presentation nationally and internationally
- Information dissemination
- Project and business development
- Technology and location marketing
- Grant and location advice

Contact:

www.hessen-nanotech.de

HA Hessen Agentur GmbH
Alexander Bracht
Project manager hessen-nanotech
Abraham-Lincoln-Straße 38-42
D-65189 Wiesbaden
Telephone +49 (0) 611 / 774-8614
Fax +49 (0) 611 / 774-8620
alexander.bracht@hessen-agentur.de

Hessisches Ministerium für Wirtschaft,
Verkehr und Landesentwicklung
Dr. Rainer Waldschmidt
Kaiser-Friedrich-Ring 75
D-65185 Wiesbaden
Telephone +49 (0) 611 / 815-2471
Fax +49 (0) 611 / 815-2228
rainer.waldschmidt@hmwvl.hessen.de

TechnologieTransferNetzwerk TTN-Hessen

- Transparency in technology available in Hessen
- Networking transfer institutions, matching the requirements of the enterprises
- Supporting enterprises in optimisation of the innovation process
- Dialogue between scientists and enterprises
- Presentation of the technology know-how of the university and research experts in a virtual technology and competence market

Contact:

www.ttn-hessen.de

HA Hessen Agentur GmbH
Dr. Gerrit Stratmann
Project coordination
Abraham-Lincoln-Straße 38-42
D-65189 Wiesbaden
Telephone +49 (0) 611 / 774-8691
Fax +49 (0) 611 / 774-8620
gerrit.stratmann@hessen-agentur.de

NanoNetzwerkHessen – NNH10^{-9}

- Coordination of the university activities in research and instruction
- Sharing of equipment and infrastructure
- Usage of the synergy potential for joint research applications
- Build-up of a powerful Nano Science-Commerce Forum and initiation of co-operative transfer objects
- Common public appearance

Contact:

www.nanonetzwerkhessen.de

Dr. Beatrix Kohnke
Project coordination
Mönchebergstraße 19
D-34109 Kassel
Telephone +49 (0) 561 / 804-2219
Fax +49 (0) 561 / 804-2226

Nanotechnology competence networks in Hessen

NanoNetzwerkHessen

Coordination of research through networking of the Hessen universities and technical colleges

www.nanonetzwerkhessen.de

CINSaT – Center for interdiscilinary Nanostructure Science and Technology

Cooperation of scientists in physics, chemistry, biology and electrical engineering at Universität Kassel

www.cinsat.uni-kassel.de

WZMW – Wissenschaftliches Zentrum für Materialwissenschaften der Philipps-Universität Marburg (Scientific Centre for Material Science)

Research focus: Material sciences with specialisation in chemistry, geosciences and physics at the University in Marburg

www.uni-marburg.de/wzmw/

Universities and technical colleges: science coordinators for NanoNetzwerkHessen

Coordination

Dr. Beatrix Kohnke
Entwicklungsplanung, E2
Mönchebergstraße 19, 34125 Kassel
Telephone +49 (0) 561/804-2219, Fax +49 (0) 561/804-2226
beatrix.kohnke@uni-kassel.de

Technische Universität Darmstadt

Prof. Dr. Matthias Rehahn
Fachgebiet Makromolekulare Chemie
Fachbereich 07
Petersenstraße 22, 64287 Darmstadt
Telephone +49 (0) 6151/16-5278, Fax +49 (0) 6151/16-4670
mrehahn@dki.tu-darmstadt.de

Johann Wolfgang Goethe-Universität Frankfurt am Main

Prof. Dr. Robert Tampé
Fachgebiet Chemie / Biologie
Institut für Biochemie
Marie-Curie-Straße 9, 60439 Frankfurt am Main
Telephone +49 (0) 69/798-29475 /-29476,
Fax +49 (0) 69/7 98-29495
tampe@em.uni-frankfurt.de

Justus-Liebig-Universität Gießen

Prof. Dr. Bruno K. Meyer
Fachgebiet Experimentalphysik 1
I. Physikalisches Institut der Universität Gießen
Heinrich-Buff-Ring 16, 35392 Gießen
Telephone +49 (0) 641/99-33100, Fax +49 (0) 641/99-33109
Bruno.K.Meyer@exp1.physik.uni-giessen.de

Universität Kassel

Prof. Dr. Hartmut Hillmer
Fachgebiet Technische Elektronik
Institut für Mikrostrukturtechnologie und Analytik
Heinrich-Plett-Straße 40, 34132 Kassel
Telephone +49 (0) 561/804-4885, Fax +49 (0) 561/804-4488
hillmer@uni-kassel.de

Philipps-Universität Marburg

Prof. Dr. Andreas Greiner
Fachgebiet Makromolekulare Chemie, Fachbereich Chemie
Hans-Meerwein-Straße, Gebäude H, 35032 Marburg
Telephone +49 (0) 6421/28-25573, -25777,
Fax +49 (0) 64 21/28-25785
greiner@staff.uni-marburg.de

Hochschule Darmstadt

Prof. Dr. Ralph Stengler
Fachgebiet Automatisierungstechnik, Messtechnik, Werkstoffkunde im Fachbereich Kunststofftechnik
Berliner Allee 61, 64295 Darmstadt
Telephone +49 (0) 6151/168562, Fax +49 (0) 661/16 8977
stengler@fh-darmstadt.de

Fachhochschule Frankfurt am Main

Prof. Dr. Werner Liedy (Ansprechpartner)
Fachbereich 2
Nibelungenplatz 1, 60318 Frankfurt am Main
Telephone +49 (0) 69/1533-2289, Fax +49 (0) 69/1533-2387
liedy@fb2.fh-frankfurt.de

Fachhochschule Gießen-Friedberg

Prof. Dr. Ubbo Ricklefs
Fachgebiet Technische Mechanik, Photonik, Bildverarbeitung
Fachbereich Elektrotechnik I
Wiesenstraße 14, 35390 Gießen
Telephone +49 (0) 641/3091914
ubbo.ricklefs@ei.fh-giessen.de

Hochschule Fulda

Prof. Dr. Alexander Osipowicz
Fachgebiet Physik
Fachbereich Elektrotechnik und Informationstechnik
Marquardstraße 35, 36039 Fulda
Telephone +49 (0) 661/9640-556, Fax +49 (0) 661/9640-559
alexander.osipowicz@et.fh-fulda.de

Fachhochschule Wiesbaden

Prof. Dr. Hans-Dieter Bauer
Fachbereich 10 – Physikalische Technik
Am Brückweg 26, 65428 Rüsselsheim
Telephone +49 (0) 6142/898-512, Fax +49 (0) 6142 / 898-528
bauer@physik.fh-wiesbaden.de

Selection of university research in Hessen in the nanotechnology field

Nanosystem technology
Technische Universität Darmstadt
Fachhochschule Wiesbaden

Nanofunction materials
Technische Universität Darmstadt
Johann Wolfgang Goethe-Universität Frankfurt am Main
Universität Kassel

Nanostructured materials
Technische Universität Darmstadt

Material development
Johann Wolfgang Goethe-Universität Frankfurt am Main

Nanomaterials
Justus-Liebig-Universität Gießen
Universität Kassel

Molecular materials
Universität Kassel

Lateral nanostructures
Universität Kassel

Nanostructuring
Johann Wolfgang Goethe-Universität Frankfurt am Main
Universität Kassel

Ultra-thin functional layers
Fachhochschule Wiesbaden

Molecular architectures
Universität Kassel

Nanomaterial chemistry
Philipps-Universität Marburg

Semiconductor structures
Philipps-Universität Marburg

Theoretical physics
Universität Kassel

Nanoelectronics
Technische Universität Darmstadt

Nanomagnetics
Johann Wolfgang Goethe-Universität Frankfurt am Main

Magnetic nanosystems
Universität Kassel

Optoelektronics
Philipps-Universität Marburg
Universität Kassel

Nanooptics
Technische Universität Darmstadt
Johann Wolfgang Goethe-Universität Frankfurt am Main
Justus-Liebig-Universität Gießen
Fachhochschule Gießen-Friedberg

Nanosensors
Technische Universität Darmstadt
Justus-Liebig-Universität Gießen
Universität Kassel
Philipps-Universität Marburg
Fachhochschule Gießen-Friedberg
Fachhochschule Wiesbaden

Nanostructure analysis
Technische Universität Darmstadt

Measurement and analysis of nanostructures
Universität Kassel

Nanochemistry
Justus-Liebig-Universität Gießen

Formulation of photocatalysts
Fachhochschule Frankfurt

Chemistry of mesoscopic systems
Universität Kassel

Process development and analytics
Johann Wolfgang Goethe-Universität Frankfurt am Main

Nanoanalytics
Justus-Liebig-Universität Gießen
Fachhochschule Wiesbaden

Nanobiotechnology
Justus-Liebig-Universität Gießen
Philipps-Universität Marburg

Nanomolecular medicine
Justus-Liebig-Universität Gießen

Nanomedicine
Justus-Liebig-Universität Gießen
Philipps-Universität Marburg

Microchips in diagnostics
Philipps-Universität Marburg

Nanopharmacology
Justus-Liebig-Universität Gießen
Philipps-Universität Marburg

VUV-Spectroscopy
Justus-Liebig-Universität Gießen

Nanophonetics
Universität Kassel

Measurement of vibrating nanosurfaces
Fachhochschule Gießen-Friedberg

Participants from Hessen in the BMBF nano competence centres

CC-NanoBioTech
Nanobiotechnology competence centre

Industrial Stakeholders / SME: None

Contact:
www.cc-nanobiotech.de
CC-NanoBioTech
Universität Kaiserslautern
Fachbereich Physik
Prof. Dr. Christiane Ziegler
Erwin-Schrödinger-Straße 56
D-67663 Kaiserslautern

CC-NanoChem Nanochemistry competence centre

Industrial Stakeholders / SME:
- Adam Opel AG, Rüsselsheim
- Degussa AG, Hanau
- Lurgi AG, Frankfurt am Main
- Merck KGaA, Darmstadt
- Siemens AG, Frankfurt am Main (formerly Siemens Axiva)
- W.C. Heraeus GmbH, Hanau
- DECHEMA e.V., Frankfurt am Main
- Technische Universität Darmstadt

Contact:
www.cc-nanochem.de
CC-NanoChem
c/o Leibniz-Institut für Neue Materialien
Prof. H. Schmidt
Im Stadtwald – Geb. 43
D-66123 Saarbrücken

Nanoanalytics competence centre

Industrial Stakeholders / SME:
- Nanosensors, Wetzlar
- Omicron NanoTechnology GmbH, Taunusstein-Neuhof
- Oxford Instruments GmbH, Wiesbaden
- Telekom Technologiezentrum, Darmstadt
- Focus GmbH, Hünstetten
- Universität Kassel

Contact:
www.centech.de
CeNTech GmbH – Münster
Dr. Frank Schröder-Oeynhausen
Gievenbecker Weg 11
D-48149 Münster

Ultra-precise surface machining competence centre

Industrial Stakeholders / SME:
- NTG Neue Technologien GmbH & Co. KG, Gelnhausen

Contact:
www.upob.de
CCN Ultrapräzise Oberflächenbearbeitung e.V.
– Braunschweig
Dr. Uwe Brand
Bundesallee 100
D-38116 Braunschweig

NanoMat

Industrial Stakeholders / SME:
- Degussa AG, Hanau
- DECHEMA e.V., Frankfurt am Main
- Merck KGaA, Darmstadt
- SusTech, Darmstadt
- Technische Universität Darmstadt

Contact:
www.nanomat.de
Nanomat - Forschungszentrum Karlsruhe GmbH
Dr. Regine Hedderich
Postfach 3640
D-76021 Karlsruhe

NanOp – Nanotechnology for optoelectronics

Industrial Stakeholders / SME:
- Akzo Nobel HPMO, Marburg

Contact:
www.nanop.de
Institut für Festkörperphysik
Technische Universität Berlin
Sekr. PN 5-6
Matthias Kuntz
Hardenbergstraße 36
D-10623 Berlin (Germany)

Ultradünne funktionale Schichten Sachsen
(Ultra-thin functional layers)

Industrial Stakeholders / SME:
- Merck KGaA, Darmstadt
- Leica Microsystems GmbH, Wetzlar
- Leybold Systems GmbH, Hanau
- Verband Deutscher Maschinen- und Anlagenbau e.V., Frankfurt am Main

Contact:
www.nanotechnology.de
Geschäftsstelle des Nano-CC-UFS im Fraunhofer IWS Dresden
Dr. Ralf Jäckel
c/o Fraunhofer IWS Dresden
Winterbergstraße 28
D-01277 Dresden

(As of 2004, partially updated)

World Wide Web links to nanotechnology

Action line "hessen-nanotech"

www.hessen-nanotech.de

Platform for nanotechnology in Hessen

www.nanotech-hessen.de

HA Hessen Agentur GmbH

www.hessen-agentur.de

NanoNetzwerkHessen

www.nanonetzwerkhessen.de

TTN-Hessen – TechnologieTransferNetzwerk-Hessen

www.ttn-hessen.de

Portal of the BMBF and VDI for nanotechnology

www.techportal.de/de/b/2/start,public,start/

Publications site of the BMBF

amongst others studies on nanotechnology
www.bmbf.de/publikationen/index.php

BMBF competence centre

- "Application of nanostructures in optoelectronics"
  www.nanop.de
- "Ultra-thin functional layers"
  www.nanotechnology.de
- "Nanotechnology: Functionality using chemistry"
  www.cc-nanochem.de
- "Ultra-precise surface machining"
  www.upob.de
- "Nanoanalytics"
  www.nanoscience.de
- "Nanomaterials"
  www.nanomat.de

Nanotechnology competence networks in Germany

www.kompetenznetze.de/navi/de/Innovationsfelder/nanotechnologie.html

Information server (Cordis) of the EU for nanotechnology in the 6th framework programme

www.cordis.lu/nanotechnology/

"Nanoforum" Web portal to nanotechnology activities in the EU

www.nanoforum.de

Web portal of the nanotechnology community

www.nanoscout.de

National Nanotechnology Initiative (NNI) in the USA

www.nano.gov

Center for Biological and Environmental Nanotechnology (CBEN) in den USA

www.ruf.rice.edu/~cben/

News portal for nanotechnology

www.nano.ivcon.org

Homepage of the National Center For Environmental Research of the U.S. Environmental Protection Agency (EPA)

http://es.epa.gov/ncer/

Occasional Paper Series

of the Aktionslinie **hessen-umwelttech** of the Ministry of Economy, Transport, Urban and Regional Development in Hessen

Information / download / orders:
www.hessen-umwelttech.de

Occasional Paper Series

of the Aktionslinie **hessen-nanotech** of the Ministry of Economy, Transport, Urban and Regional Development in Hessen

Volume 1 **Uses of Nanotechnology in Environmental Technology in Hessen**
Innovation potentials for companies (jointly with the Aktionslinie hessen-umwelttech)

Volume 2 **Nanomedicine**
Innovation potentials in Hessen for medical technology and the pharmaceutical industry
(jointly with the Aktionslinie hessen-biotech, only in German language)

Volume 3 **NanoAutomotive**
Innovation potentials in Hessen for the automotive industry and its subcontractors (only in German language)

Volume 4 **NanoCommunication**
Guide to communication of chances and risks for small and medium-sized nanotech companies in Hessen
(only in German language)

Volume 5 **NanoOptics**
Nanotechnologies for the optical industry. A basis for future innovations in Hessen (only in German language)

Volume 6 **NanoProduction**
Nanotechnology in the production process as a potential innovation source for companies in Hessen
(only in German language)

Informationen / download / orders:
www.hessen-nanotech.de

hessen » Hier ist die Zukunft
nanotech
umwelttech

www.hessen-nanotech.de
www.hessen-umwelttech.de

Fraunhofer IAO
Institut
Arbeitswirtschaft und
Organisation

Projektträger der Aktionslinien
hessen-nanotech und **hessen-umwelttech**

HESSEN
HessenAgentur
HA Hessen Agentur GmbH