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Nanotechnologies, Hazards and Resource Efficiency

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A Three-Tiered Approach to Assessing the Implications of Nanotechnology and Influencing its Development

with 53 Figures

Springer

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The Autors

Preface

Nanotechnology is frequently described as an enabling technology and fundamental innovation,[1] i.e. it is expected to lead to numerous innovative developments in the most diverse fields of technology and areas of application in society and the marketplace. The technology, it is believed, has the potential for far-reaching changes that will eventually affect all areas of life. Such changes will doubtlessly have strong repercussions for society and the environment and bring with them not only the desired and intended effects such as innovations in the form of improvements to products, processes and materials; economic growth; new jobs for skilled workers; relief for the environment; and further steps toward sustainable business, but also unexpected and undesirable side effects and consequences.

With respect to the time spans in which nanotechnology's full potential will presumably unfold, M. C. Roco (2002:5)[2] identified the following stages or generations for industrial prototypes and their commercial exploitation:

- **Past and present**: The "coincidental" use of nanotechnology. Carbon black, for example, has been in use for centuries; more specific, isolated applications (catalysts, composites, etc.) have been in use since the early nineties.
- **First generation**: Passive nanostructures (ca. 2001). Application particularly in the areas of coatings, nanoparticles, bulk materials (nanostructured metals, polymers, and ceramics).
- **Second generation**: Active nanostructures (ca. 2005). Fields of application: particularly in transistors, reinforcing agents, adaptive structures, etc.

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[1] In the more recent literature, "system innovation" is most often used. For literature on nanotechnology in general; see for example (Bachmann 1998) as well as (National Science and Technology Council 1999) and (NNI 2000).

[2] In place of Roco (2002) other authors and studies, each with its own time scale, could have been named. This is unimportant for our purposes here, as we first and foremost want to call attention to the dynamics of the developments over time.

- **Third generation**: Three-dimensional nanosystems (ca. 2010) with heterogeneous nanocomponents and various assembling techniques.
- **Fourth generation**: Molecular nanosystems (ca. 2020) with heterogeneous molecules, based on biomimetic processes and new design.

It must come as no surprise that the revolutionary potential of nanotechnology has also led to some somewhat extreme judgments. There is, for example, the "radical green vision," in which nanotechnology will help to solve all environmental pollution problems; then there is the radical horror scenario ("grey goo"), according to which all life on earth will be destroyed by nanobots gone wild.[3] Looking beyond these two extremist scenarios, one ultimately finds fully justifiable societal controversies concerning the direction of development and the opportunities and risks associated with the realization of the tremendous technological potential in the nanoscale domain. A great deal of the controversy revolves around the ecological and economic – not to mention health and social – consequences of nanotechnological development and ideas for the future.

Public discourse and the early dissemination of extensive information on technological consequences and the impact of nanotechnology on sustainability are not only advisable, but therefore necessary. In Germany, three projects for an analysis of the innovation and technological potential of nanotechnology on the following topics have accordingly been carried out:

- The Economic Potential of Nanotechnology; Contractor: VDI Zukünftige Technologien Consulting, Düsseldorf; Deutsche Bank Innovationsteam Mikrotechnologie, Berlin
- Nanotechnology and Health; Contractor: Aachener Kompetenzzentrum Medizintechnik (AKM), Institut für Gesundheits- und Sozialforschung Berlin (IGES), among others.
- Effects of the Production and Application of Nanotechnology Products on Sustainability; Contractor: Institut für ökologische Wirtschaftsforschung (IÖW) in cooperation with the Universität Bremen, asmec GmbH, and Nanosolutions GmbH

The project "Effects of the Production and Application of Nanotechnology Products on Sustainability" addresses the current state of materials and technology assessment and attempts to develop this further toward an integrated prospective sustainability assessment. The focus is therefore on the environmental opportunities and risks in this developing technology.

Inasmuch as nanotechnology is a broad, extremely heterogeneous technological field, a generally accepted definition for it still does not exist.

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[3] See (Joy 2000; etc group 2002)

This study, therefore, is oriented on Paschen et al. (2003) and Basler & Hofmann (2002) and utilizes the following definition of nanotechnology:

Nanotechnology deals with structures in which at least one dimension is smaller than 100 nm. Nanotechnology takes advantage of characteristic effects and phenomena that arise in the transition region between the atomic and mesoscopic levels. Nanotechnology denotes the selective fabrication and/or manipulation of individual nanostructures.

The project takes up two main questions:

1. How can one successfully evaluate the to-be-anticipated effects of a technology still in the making?
2. How can we successfully influence sustainable development in nanotechnology design?

When a technology's applications are still not fully known, and – as in the case of nanotechnology – there are good reasons to assume that new, unknown effects exist, the only significant variable that remains for investigation is the technology itself. It is therefore advisable to turn our attention from the "effects" to the "cause," i.e., to an analysis and characterization of nanotechnology itself. Furthermore, by concentrating on already known concrete applications, sustainability effects can be collected and assessed using a life cycle assessment approach. Therefore the in-depth case studies particularly address applications utilizing nanoparticles and nanostructured surfaces. Furthermore, new technologies do not simply "grow," in a natural manner, but are instead developed by individuals, each acting of their own accord, using the means available to them, and working in recognizable constellations (innovation systems). New technologies are therefore "formed" and in this process the Leitbild (a concept often translated as "exemplary or formative model," "target concept," or "guiding vision") often plays a significant role. With respect to the second question, we therefore consider the possibilities as to whether and to what extent the help of such Leitbilder and other means can influence the development of nanotechnology.

This book is an updated version of our project report and has the following structure: In the chapters that follow, the results of the studies are summarized. In chapter two the methodological basis for a three-stage approach to prospective technology assessment and development of nanotechnology is introduced. In chapters three through five we present the results that were achieved with the help of this method. Chapter six concludes with a summary of the results, preliminary scientific conclusions, and suggestions for further needed research.

Contents

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1 Summary

This project, “Effects of the Production and Application of Nanotechnology Products on Sustainability,” was funded by the German Federal Ministry of Education and Research and addresses the current state of materials and technology assessment and attempts to further development toward an integrated prospective sustainability assessment. The focus is on environmental opportunities and risks of the developing nanotechnologies. The project asks two main questions:

1. How can one successfully assess the to-be-anticipated effects of a technology still in the making?
2. How can we successfully influence sustainable development in nanotechnology design?

In order to do justice to the complexity of the problem definition, the following three-step approach to the prospective assessment of technology and the development of nanotechnology was utilized in the project.

- **1st approach – prospective**
  Assessment of nanotechnology and its to-be-expected effects by means of a characterization of the technology.
- **2nd approach – concurrent**
  Evaluation of sustainability effects utilizing life cycle assessment methods (extrapolating) on typical applications in comparison to existing products and processes.
- **3rd approach – formative**
  Leitbilder as “guiding instruments” in technology development, associated processes, actor-specific concepts.

1.1 Characterization of some nanotechnologies

Every form of engineering results assessment has to struggle with the prognosis problem and deal with lack of knowledge (the unknown or unknowable), and uncertainty. The prospective-oriented approach focuses on the assessment of nanotechnology and its anticipatable effects by means of a "characterization of the technology" (described in detail in Gleich 2004). Awareness of and serious consideration of the problem of the unknown in the development of new technology makes it possible with such a characterization to derive and describe possible risks as well as positive effects.

Nanotechnological processes are first and foremost characterized by the dimension in which they take place. In the nanoworld we are at the level of individual molecules and atoms, in a realm measured in millionths of a millimeter. An example of what makes this dimension special is the behavior of nanoparticles, which is generally quite different from that of their more coarse-grained counterparts. For example, the large specific surface area of nanoparticles leads, as a rule, to an increase in chemical reactivity and/or catalytic activity. The relatively small number of atoms in nanoparticles leads, on the other hand, to deviations in optical, electrical, and magnetic properties. Beyond these fundamental characteristics of nanotechnology, other positive effects and potential benefits and/or possible, anticipatable problematic effects can be derived.

Table 1. Characteristics of nanomaterials and thus anticipatable positive ecological benefits or potentials and/or problematic effects[4]

Nano-characteristic		+ Positive environmental impact and benefits / - Problems and hazards	Assessment approaches
Small particle size and particle mobility	+	Selective use for resource- and eco-efficient technology	Life cycle assessment (LCA), dispersal and exposure models, (eco-) toxicological testing, animal testing, epidemiology
	-	Absorbed by the lungs and alveoli Passes through cell membranes, via the olfactory nerve directly into the brain Mobility, persistence and solubility as indicators for bioaccumulation and environmental hazard	
Precision, particle size / layer size, purity	+	Selective use for resource- and eco-efficient technology	LCA, entropy balance, question of "ecological amortization"
	-	Increased production costs, higher material and energy streams, increased use of resources	
Material characteristics	+	Possible replacement for substances dangerous to health and environment	Toxicology, ecotoxicology,

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[4] Source: Based on (Gleich 2004) and (Steinfeldt 2003)

	-	Health and environmental dangers due to hazardous (rare) elements or substance groups in environmentally open applications	relationship between “natural” and “anthropogenic” material streams
Adhesion, cohesion, agglomeration	+	“Intrinsic safety” due to adhesive, cohesive, and agglomerative tendencies of nanoparticles, thus loosing their nanocharacteristics	Dispersal and exposure models, (environmental) (eco-) toxicology testing, animal testing, epidemiology, atmospheric chemistry, risk analysis
	-	Behavior of nanoparticles or fibers “set free” in the environment Mobilization and inclusion effect of nanoparticles on toxins and heavy metals (piggybacking)	
New chemical effects, modified behavior	+	Utilization of modified behavior for resource and environmentally efficient technology, e.g. use of catalytic effects for more efficient chemical processes or in the environment	LCA, dispersal and exposure models, (eco-) toxicology testing (e.g., allergy / sensitization testing), animal testing, epidemiology, atmospheric chemistry, risk analysis
	-	Changes in: solubility, reactivity, selectivity, catalytic and photocatalytic effects, and temperature dependence of phase transitions mean that surprising technological, chemical, toxicological, and environmentally toxic effects can be expected	
New physical effects, modified optical, electrical, magnetic behavior	+	Selective utilization of effects and modified properties for resource and environmentally efficient technology, e.g.GMR effect, Tyndall effect, quantum effects, tunnel effect	LCA, for technological systems: FMEA, fault-tree analysis
	-	Generally dependent on purified, precisely regulated “technical environments”; there (in the case of non-compliance) surprises can be expected (technical failure)	
Self-organization	+	Selective use for resource / eco-efficient and consistent technology	Risk analysis, depth of intervention, LCA, environmental impact analysis, scenario techniques
Self-replication	-	Danger of uncontrolled developments, self-reproducing nanobiostructures	

This characterization overview makes clear that with the new properties of nanoparticles many hazards could arise, particularly when handled in an open environment. This issue, also of the highest priority in the current discourse on risks, was therefore separately addressed in an in-depth case study.

In an assessment of the hazards of further applications – in part, far in the future – in the area of self-organization (particularly combinations of nanotechnology and biotechnology, and possibly nanotechnology and robotics), the aspect of possible self-replication or reproduction becomes much more significant. However, it must be noted that the potential for self-replication presented by a fusion of nanotechnology and biotechnology or genetic engineering may much more likely than that based on a merger of nanotechnology and robotics. The capability of self-replication such as that possessed by genetically modified organisms may anyhow open up new hazards with respect to health and environmental dangers; whereas this is less of a hazard for pure self-organization. As long as nanotechnology limits itself to dealing with molecules, such a step from the self-organization of molecules to self-replication and copying of organisms (or assemblers) – unless intentionally pursued – is rather unlikely. However, with the merger of nanotechnology and the genetic modification of organisms capable of self-reproduction, such a step could be entirely feasible.

This characterization of nanotechnology at the technological level, which certainly looks ahead to developments far in the future, was followed by a qualitative analysis of currently relevant manufacturing processes for nanoparticles and nanostructured materials in this already particularly well-developed area of nanotechnology, specifically chemical vapor deposition, the Siemens-Martin (open hearth) and sol-gel processes, precipitation, molecular imprinting, lithography, and self-organizing processes – e.g., self-assembled monolayers (SAMs) – with respect to their technological and thereby associated energy and material expenditures as well as their potential risk for the release of nanoparticles.

In contrast to other processes, these all possess a higher potential for the release of nanoparticle emissions in a gaseous form, which could lead to direct emissions in the workplace and the production of loose nanoparticles, for example, in flame-assisted deposition. In other processes, the risks are judged to be rather minimal, assuming that the resulting emissions are adequately handled by an appropriate exhaust air or waste water treatment facility capable of inhibiting the emission of nanoparticles. Furthermore, some of the process technologies presented, such as those that have already been implemented as fundamental technologies in microelectronics and optoelectronics, are notable for an immense technical and energy expenditure yielding a rather small absolute quantitative output.

1.2 Evaluation of specific application contexts

Building on this characterization of specific nanotechnologies and their manufacturing processes to date, the ongoing extrapolative assessment approach tracks the investigation of sustainability effects using specific application examples that are compared to existing products and processes. In this process, the focus was placed on environmental opportunities and risks.

As an assessment approach, the prepared environmental profiles are modeled on the life cycle assessment methodology. The life cycle assessment (LCA) is the most extensively developed and standardized methodology for assessing the environmental aspects and product-specific potential environmental impacts associated with the complete life cycle of a product. It has the advantage that by means of comparative assessments, an (extrapolative) analysis of eco-efficiency potential in comparison to existing applications is possible. With its method of extrapolation, however, this study goes far beyond the current state of the methodology. At the same time, the LCA methodology – as with all methodologies – has its characteristic deficits; there are impact categories for which generally accepted impact models and quantifiable assessments do not exist. This is particularly true in the relevant categories of human and environmental toxicity. And so, a consideration of the impact of fine dust particles (the PM-10 risk, for example, deals with the potential toxicity of particles smaller than 10 µm) in assessments of nanotechnology applications is therefore already doomed to failure because of its reference to material flows expressed in weight. Furthermore, in LCA assessments the risks and the technological power (hazard) effectiveness of applications are not considered. A comprehensive methodology must provide for such analyses.

In the project an attempt was therefore made to compensate for these methodological shortcomings through the establishment of priorities in the selection of the specific application contexts. From the spectrum of all nanotechnology applications, four case studies were chosen in which, on the basis of a preliminary assessment and qualitative evaluation, particularly interesting eco-efficiency potentials could be expected. A further constraint in the selection of the case studies resulted from the requirement that only those examples be considered for which LCA data was (at a minimum) already available for the enlisted "conventional" technologies or products to be used in the comparison. The potential risks and hazards in those nanotechnology applications that were not considered were then analyzed and considered in a separate hazard analysis focusing specifically on nanoparticles.

Table 2. Overview of the case studies investigated

Application context	Goal
Eco-efficient nanocoatings	Presentation of the eco-efficiency potential of nanocoatings in the form of a comparative ecological profile (Nanocoating based on sol-gel technology as compared with waterborne, solventborne, and powder coat industrial coatings)
Nanotechnological process innovation in styrene production	Presentation of the eco-efficiency potential of nanotechnology in catalytic applications in the form of a comparative ecological profile (Nanotube catalyst as compared with iron oxide–based catalysts)
Nanotechnological innovation in the video display field	Assessment of eco-efficiency potential in video display development by means of a qualitative comparison (Organic LED displays and nanotube field emitter displays as compared with CRT, liquid-crystal, and plasma screens)
Nano-applications in the lighting industry	Presentation of eco-efficiency potential of nano-applications in the lighting industry in the form of a comparative ecological profile (White LED and quantum dots as compared with incandescent lamps and compact fluorescents)
Potential risks of nanotechnological applications involving nanoparticles	Discussion of possible risks and harzards using titanium dioxide as an example; less a consideration of environmental impact

The results of the LCA comparisons make clear that nanotechnology applications neither intrinsically nor exclusively can be associated with the potential for a large degree of environmental relief. Nevertheless, for the majority of the application contexts – selected with these aspects in mind – significant eco-efficiency potentials could be ascertained using the chosen methods of comparative analysis of functionality.

The reliability of the ascertained numbers is, of course, dependant on the quality and accessibility of the material and energy data available for the individual applications. For those nanotechnological processes still in development, almost no quantitative evidence is available, although for the usage phase estimates (mostly in energy-savings potential) are possible. Likewise, when comparing established or mature technologies with those still in development, one must recognize that the new technology is at the beginning of its "learning curve," i.e., that it holds the potential for significantly greater increases in efficiency.

The case study "**Eco-efficient Nanocoatings**" makes impressively clear that in the field of surface coatings, with respect to all emissions and environmental considerations studied; there is great potential for a very high degree of eco-efficiency through the utilization of nanotechnology-based coatings. It was also possible to demonstrate the further advantages of a simplified pretreatment process (no chromating). The minimal coating thickness necessary to achieve the same level of functionality makes possible a five-fold increase in resource efficiency. Advantages in the use phase are particularly to be expected in the transport sector as the trend to lighter-weight fabrication continues. In addition to the automotive industry, the potential for greater efficiency will have an even greater effect on the airline and rail industries. A further potential for optimization can be found in the reduction of the proportion of solvents in nanocoating applications.

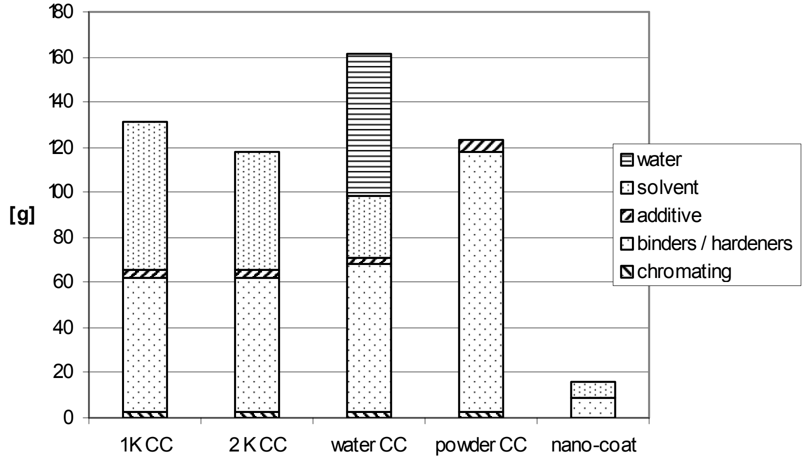

Fig. 1. Coating and chromating quantities (g/m^2 coated aluminum automobile surface area)[5]

In the course of the case study "**Nanotechnological Process Innovation in the Production of Styrene**," we took as our example for investigation the ecological potential of nanotechnology-based catalytic applications. Specifically, the deployment of a nanostructured catalyst based on nanotubes for the chemical production (synthesis) of styrene. Since no detailed

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[5] Source: authors (base data: authors, Harsch and Schuckert 1996)

life cycle assessment data for this alternative styrene production process was available, data on the energy use for this process were derived from descriptions of the technology.

The alternative styrene production process, based on a nanotube catalyst, thus yielded potential energy savings of almost 50% at the process stage. Two special effects are responsible for this improvement in efficiency: first, the previously endothermic reaction could be converted to an exothermic one; second, the reaction temperature could be lowered considerably, the reaction medium altered, and the plant power input minimized. With regard to the overall styrene product life cycle, this means an increase in efficiency of about 8−9%. Furthermore, the new catalyst makes possible considerable reductions in heavy metal emissions during the product life cycle. Possible risks from the deployment of nanotubes could negatively offset this; this still needs to be further investigated and taken into consideration in possible facility planning.

The goal of the case study “**Nano-innovations in Display Technology**” was the investigation of possible eco-efficiency potentials in the transition to new nanotechnology-based displays that just now are in the early stages of development. In this case study, OLEDs as well as CNT FEDs were compared to conventional CRT and modern LCD and plasma displays.

This case study likewise suggests that increases in material and energy efficiencies are possible, although due to the various stages of development of the technology, the resulting eco-efficiency estimates come with a certain degree of uncertainty. After overcoming the problem of long-term stability of the organic luminescent materials, the lower production costs of OLEDs as compared to those of the prevailing LCDs could stand in their favor. OLEDs also promise a greater degree of energy efficiency in the use phase (by a factor of two as compared to the LCD). The successful implementation in mass production of these material and energy increases in efficiency will make possible significant eco-efficiency potentials. A minimum twenty-percent savings in life-cycle energy use as compared to the LCD seems possible.

The development of higher eco-efficiency potentials for CNT FEDs will also be possible once energy efficiencies in the manufacturing phase, particularly the highly complex production of nanotubes for field emitters, becomes comparable to current production processes. Risks from these new technologies are unlikely.

Our goal in the case study “**Nano-applications in Lighting**” was to investigate possible eco-efficiencies by means of the application of new nanotechnological products in the field of illumination. White LEDs were compared to conventional incandescent and compact fluorescent lamps; furthermore, the future potential of quantum dots was also investigated.

With light sources in use today, 97−99% of the life-cycle energy consumption occurs in the use phase. Materials consumption, in comparison, is of much lesser consequence. The crucial measure for the environmental assessment of light sources used as illumination, therefore, is energy consumption and associated emissions during the use phase. The current white LED, it turns out, compares favorably to the conventional incandescent lamp, but is at a disadvantage by a factor of three when compared to the compact fluorescent. Only with the further development of nanotechnology-based products with a significantly higher light efficiency, i.e., white LEDs with an efficiency above ca. 65 Im/W, will the LED become environmentally comparable to the compact fluorescent and useful in non-specialized lighting applications, i.e., for everyday lighting purposes.

The use of quantum dots as source of illumination will someday make possible even greater increases in energy efficiency. Quantum-dot technology is expected to find long-term application in the area of video displays, particularly in combination with OLEDs. However, the commercial application of quantum dots is still some years away.

The case study "**Risk Potentials of Nanotechnological Applications**" specifically focuses on the analysis and consideration of the potential risks of nanoparticles. In this study we explore the hazards that could arise due to the properties of the structures, substances, and materials utilized in the field of nanotechnology. We also give an account of the problematic effects for humans and the environment of selected nanoparticle structures and materials as already described in the scientific literature.

The behavior of nanoparticles is, in part, quite different from that of the same materials at the macro level; this is true even for identical compounds. Some extremely surprising effects and properties of nanoparticles and nanostructured surfaces can be found in many of the studies analyzed. They document a series of suspicious factors with respect to the possible toxic effects of nanomaterials and – particularly nanoparticles – on the environment and human health, all of which need to be seriously addressed. In addition to the essentially structureless nanoparticle, nano-structured materials such as nanotubes and buckyballs are of particular significance here.

However, the scientific results so far are preliminary in most cases and in part contradictory and they often consider only a small fraction of possible effects. The degree to which generalizations can be made or knowledge carried over from these individual studies is extremely questionable. The current state of knowledge is far too sketchy for a thorough risk assessment. Generalizations and toxicity classifications for nanoparticles appear to be possible in, at best, a medium-term time span.

Furthermore, the previous results relate principally to human-toxicological questions. We still know almost nothing about the ecotoxicity and behavior of nanoparticles in the environment. Much broader research is sorely needed. Taking into consideration production processes and the majority of applications, the issue of risks today, with respect to nanoparticles, does appear to be pressing, but of possibly limited scope if releases into the environment can be avoided. A point in favor of this is that many production processes occur in either an aqueous solution or in a closed system and, in many products, the particles or nanostructures are firmly bonded in a matrix. Nevertheless, over the course of the entire life cycle there still exist large gaps in our knowledge with respect to risk potentials.

1.3 Formative approaches to sustainable nanotechnology

Steering technological development by means of political intervention is either impossible or possible only to a very limited extent in complex modern societies. In spite of this, the course of such development is anything but chaotic. On the contrary, out of the interactions of the most varied agents a comparably stable course of development is often the result, one which can be accompanied in a formative way. The significance of independent paths of technological development over the course of time and the opportunities that these offer for the early identification of adverse effects on the environment and our health, and in-turn, for the timely assertion of influence, is depicted in the following illustration.

The following illustration makes clear that throughout the entire process, from basic and applied research through the development, use, and disposal phases, appropriate precautionary options can and must be developed; these options can then also be applied to further research and can also be influenced, as necessary through the use of Leitbilder. In each of the various phases, various players are (collectively) responsible. This can begin in the basic research phase on the basis of scientific paradigms whose results can subsequently lead to research and development efforts (research programs) in the area of applied research. It is our view that the most far-reaching opportunities to avoid potential environmental and health risks are to be found in these early phases of scientific and technological developments.

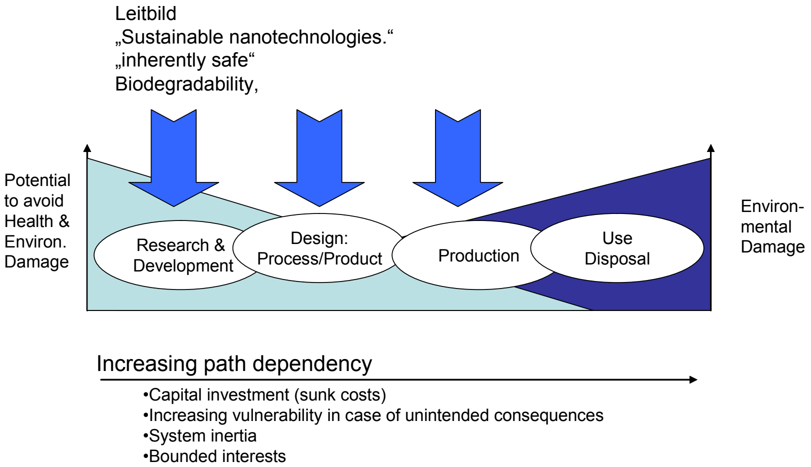

Fig. 2. Windows of opportunity for shaping technological development in the product life cycle[6]

The subsequent production process and product design phases are, in a sense, already predetermined inasmuch as they have as their foundation the imprint or character of the initial research and development phase. At the same time, there is a still relatively large degree of flexibility in process and product design that can be decisive for aspects such as “intrinsic safety” and/or possible environmental and health impacts in the subsequent phases. The options are more limited, but nevertheless still possible to a large extent.

In comparison, the number of options for shaping development in the production process and, thereafter, during use, and finally, disposal are much more limited. As a rule, at this point additional measures can still be implemented by means of the hazardous substance categories in product safety sheets, which regulate the handling of processes and products, or through the enforcement of disposal regulations.

In addition to the scientific and technical paradigms and development characteristics, the momentum acquired through the ever increasing lock-in of development pathways is also significant; this momentum arises, for example, from the participating investments involved and associated know-how and knowledge.

Scientific research on innovation and technological development has validated the importance of the Leitbild for the development of paradigms and technological trajectories (pathways) as well as for scientific revolu-

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[6] Source: based on Rejeski et al. (2003)

tions and technological changes. Leitbilder motivate the formation of a group identity that serves to coordinate and synchronize the activities of individual players, reduce complexity, and structure perception. Among the most important prerequisites for their effectiveness, therefore, are vivid imagery and emotionality, their function as a guiding vision, as well as their relationship in equal proportion to vision and feasibility; in short, their degree of resonance in the minds of the players. Visual imagery plays an important role in clarification and the associated reduction of complexity. Above and beyond emotional value and content, the Leitbild motivates and provides direction. The Leitbild, therefore, can have a controlling or guiding effect and help to define the aims and direction of innovation. In this respect, it is possible to explore opportunities for steering innovation toward sustainable development with the help of Leitbilder. In the course of this project, three specific suggestions for sustainable nanotechnology Leitbilder, of varying scope, were developed: “Resource-efficient Nanotechnology,” “Consistent and Intrinsically Safe Nanotechnology,” as well as the long-term oriented Leitbild “Nanobionics.”

In the various phases of the product life cycle (see Fig. 2), the various players that are involved in the design and whose negotiations are significant for the potential impact of the product or process each take their turn. Achievement of optimizations related to the product life cycle requires that communication channels exist between the various players along the entire value chain. With the exception of large firms that have comprehensive management systems or firms situated in adjacent production stages and capable of taking on the “system management” for the entire production chain, these communication channels are presently lacking in many areas. Communications channels along the value chain – and more so between the players and those possibly affected at the end of the product cycle – are often limited or not yet developed in the early phases of product development.

The most diverse institutions and circles of players are involved along the value chain; each alone has only limited opportunities for action, but through cooperation these opportunities can be significantly expanded. In principle, what one has is a typical governance problem in which the influences and possibilities for influence by the various players in the design and development process are not clearly perceived or assignable. As a result, in addition to the prognosis problem of the (prospective) technology assessment, with a view to the possible consequences of an emerging technology we also must consider the problem of complexity with respect to potential opportunities for influence. The possible consequences of innovations based on nanotechnology are, as already described, only predictable to a limited extent. The possibilities for steering or influencing each of the players or groups of players on an individual basis are, on the one hand, decisively affected by the individual dynamics of their social sub-systems, and on the other hand, limited by the developmental dependencies (lock-ins). It is important to create more flexible subsystems that react in a less compartmentalized fashion, but at the same time, it is important to exhaust the entire repertoire of possibilities for moving the market toward sustainability.

Therefore, in addition to the role of Leitbilder as potential instruments in technological development, further formative approaches and developmental instruments were outlined:

- The integration of safety, health, and environmental aspects in comprehensive quality management extending throughout the value chain.
- Sustainability-oriented nano-design in commercial research and development.
- Federal regulatory approaches

In view of the enormous prognosis problem with which the engineering results assessment has to struggle (even if the approaches arising out of the technology characterization have largely been exhausted), the importance of the concurrent approaches to specific development of nanotechnology or products and processes based on it must be emphasized. Along with those methods already introduced, related approaches such as constructive technology assessment (CTA) and real-time TA are also to be considered.

1.4 Conclusion and need for action

In the course of a three-stage approach, technology-characterization has made possible the identification of substantial hazards associated with some nanotechnologies – particularly in the case of nanoparticles and the possibility of a shift from self-organization toward self-replication – (hazard characterization), life cycle analysis has demonstrated potential opportunities for efficiency increases through selected applications of nanotechnology, and finally, basic approaches to sustainability-oriented design have been drafted. Among the significant conclusions that can be drawn from the study is, first of all, that potential risks from nanoparticles in non-contained applications already exist today and should not be ignored. Secondly, the results of the life cycle assessment demonstrate that the potential for significant environmental relief can be exploited, but that this does not fully apply to all areas of application and may entail calculated efforts. The technology characterization and the prospective (extrapolative) or concurrent life cycle assessment have also proven themselves as practical evaluation approaches, even for technologies, products, and processes still in development. Finally, it must be noted that Leitbild-oriented design – not in the least because of the findings in the first two approaches – will play an important role in further development of the technology toward sustainability.

At the operative level, in addition to the working with Leitbilder, the assessment, information, and communication instruments already mentioned here seem to be fundamentally well-suited for generating guidelines for action, particularly for small and mid-sized businesses (guidelines, development directives, management systems, etc.).

- Here, as a rule, the early phases of scientific and technological development offer the greatest opportunities for working toward sustainability; however they must be exploited. The development of formative Leitbilder offers itself as a valid approach.
- This should be augmented by concurrent and design-oriented processes, such as constructive technology assessment (CTA) or real-time technology assessment. Open communication processes throughout the entire value chain and product life cycle should be incorporated into scientific, business, and social organizations. Roadmaps for nanotechnological development represent another suitable instrument for integration and direction. Extrapolative life-cycle assessments – as presented here – should also be utilized and their results should be reflected back into the processes.
- As players in these processes, businesses have a substantial responsibility, which – particularly in newer EU environmental policy approaches such as REACh or in Integrated Product Policy (IPP) – have been repeatedly emphasized. The approaches mentioned assume at least a shared responsibility and in that respect take industry up on its promise. The development of integrated management concepts extending across the entire value chain, in which the aspects of health, safety, and environment (HSE) are recognized as quality assurance elements, would be a help. For the support specifically of small and medium-sized businesses, guidelines for nanotechnology-based sustainability-oriented design of products and processes would be tremendously useful in this context.

In addition to further development of such instruments, there is above all the ongoing need for further research. With respect to the assessment of nanotechnology hazards and risks, the need for research is particularly great with regard to:

- toxicological and ecotoxicological analyses within the framework of integrated research programs

- the systematization and classification of nanoparticles
- the behavior of nanoparticles and nanostructured surfaces in environment

Above and beyond the case studies investigated, which were very much focused on inorganic application contexts, there is a need for further research, particularly:

- with respect to still-to-be-completed or much further-reaching eco-efficiency potentials through the use of the principles of self-organization in the nanoscale dimension – in the inorganic as well as organic fields.
- with respect to a possible initial mid-to-long-term insidious transition from self-organization to self-reproduction in the areas of “active nanosystems” as well as particularly in the course of a possible coalescence of nano- with bio- or gene technologies.

It should furthermore be noted that future environmental assessment considerations of nanotechnological applications would be made significantly easier if material and energy flows (i.e., essential assessment data) for the relevant manufacturing methods were more easily accessible (or made accessible at all) and, if necessary, centrally collected.

If widely held expectations for nanotechnologies (and the innovations to be derived from them) are to be realized with respect to making significant contributions toward a sustainable economy, the approaches to a commensurate shaping of the processes, as described here and elsewhere, must be seriously considered. The potential benefits of nanotechnologies will not simply fall into our laps, but must be pursued with deliberation and effort. With this in mind, it is essential that technology, process, and product development be further accompanied by ongoing, concurrent assessment, with a view to precautionary risk management as well as to the effective utilization of the potential for sustainability benefits that are unquestionably associated with this line of technology.

2 Methodological approaches to the prospective assessment

In order to do justice to the complexity of the project's requirements, a three-step approach to prospective technology assessment and development of nanotechnology was followed.

- 1st Approach – prospective
  Technology characterization: Assessment of nanotechnology and its anticipatable effects by means of a characterization of the technology.
- 2nd Approach – process-concurrent
  Extrapolative life cycle assessment: Evaluation of sustainability effects utilizing life cycle assessment methods with specific current (already or about to be realized) applications in comparison to existing products and processes.
- 3rd Approach – formative
  Possibilities and limitations of the Leitbild approach: Leitbilder as a tool for directing technology development; accompanying processes and actor-specific concepts.

2.1 Characterization of technologies

2.1.1 Dealing with the unknown

Each and every engineering results assessment must struggle with the prognosis problem. How can problematic developments in technology be assessed; how do we record risks, secondary effects, and impacts that are entirely unknown? The prognosis problem in technological assessment has recently been further accentuated by the extensive attention being given to the problem of dealing with the unknown and the uncertain (cf. Wehling 2001; Böschen 2002; Wehling 2002). Generally speaking, there are two forms of the unknown:

1. The still-unknown. This is knowledge that, in principle, is acquirable, but not yet available, for example, because specific tests have not yet been conducted or specific know-how has not yet been acquired. There can be many reasons for this; it could be that a potential problem could not be anticipated because it had never occurred before and the impact model had not yet been fully worked out (the ozone-destructive impact of CFCs is a prominent example). All in all, it may well be the lack of resources (time, money, qualified personnel) that plays the central role in the still-unknown. A good example can be found in the almost 100,000 so-called "existing substances," which have not yet been tested for specific effects in accordance with chemical regulations.[7]
2. The unknowable. Here the limitations of knowledge lie not with the observer but rather in the realm of the object – that which is being observed. The reactions of unstable, complex, or dynamic systems to an intervention are basically unpredictable.[8] The reasons for this unknowability lie substantially in the architecture or instability of the system where the intervention is occurring. Of course, the intensity of the intervention (in quality and quantity) can (and, as a rule, will) further amplify this problem. Examples of extreme limitations on knowability include the oft-cited flutter of the butterfly's wings that in an extremely unstable weather system can set loose a tornado; unforeseeable reactions to gaps in food chains in ecological systems; and the unforeseeability of sporadic, spatially, and temporally isolated effects of climate changes (the Gulf Stream effect, for example).

Against this background, the prognosis problem in technological assessment becomes even more critical. How can one decide between and deal with these forms of the unknown? One possibility would be the selected application of a well-thought-out, systematic trial-and-error strategy, for which we will subsequently establish some initial approaches.

Even though it may be difficult for us as scientists to accept: Certainty is the exception! Uncertainty and incomplete knowledge is the rule. However, the difficulties in appropriately dealing with this situation are by no

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[7] Approx. 3,000 of these existing substances are produced in Europe annually, with a volume of more than 1,000 tons per year. Only about 200 substances have been tested since 1981, when the law on chemical pollution came into force. This apparent failure is a major reason behind the re-alignment of European chemical pollution policy presently underway in accordance with the REACh approach, initiated by the EU white book on toxic chemicals. (cf. Europäische Kommission 2001).

[8] The ecosystem researcher Holling therefore refers in this case to "inherent unknowability"; cf. (Holling 1994)