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Nanotechnology and Sustainability

Discussion Paper of the IOEW 65/04

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Abstract:
The expected future social and economic benefits linked to the area of nanotechnology will also have to include sustainability effects. This article outlines and presents an approach to prospective technology assessment and shaping and critically discusses results of the implementation of this approach to nanotechnology applications.

Nanotechnology applications possess a large future potential for eco-efficiency. Nonetheless, potential risks resulting from adverse effects should certainly not be neglected. It is ostensibly the early stages of nanotechnology development that bear enormous leverage on the shaping of nanotechnology applications in line with future sustainability.

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Table of contents

Table of graphs

1. Introduction

Nanotechnology is often termed a system innovation, implying that it is expected to initiate an increasing number of innovative developments in various sectors of technology, various social areas of applications and economic sectors. The far-reaching possibilities of nanotechnology development, which are currently being assessed according to feasibility, find their echo in partly extreme judgements of the technology. One finds radical green visions, which proclaim the overcoming of all environmental burdens. But the uncontrollability of nanotechnology, especially in a long-term perspective, is also deemed critical (Joy 2000, etc 2002).

Those two strands of discussion are ultimately linked to social controversies over the direction of future nanotechnology development. These debates include the ecological and economic as well as the social consequences of nanotechnology development and visions.

1.1. The research project: Sustainability effects through production and application of nanotechnological products.

To begin with, current scientific debates about substance- and technology assessment were reviewed and extended towards integrated sustainability assessment. Central focus was given to possible ecological relief and possible ecological risks[1].

Two questions were central to the project:

1. In which way can possible effects of a technology be evaluated if it is still newly emerging and far from being fully developed?
2. How may active shaping of nanotechnology towards sustainability take place successfully?

If real-world applications of an emerging technology are mostly unknown and unexpected properties are to be presumed at the same time, what remains for systematic scrutiny is the technology as such. To answer the two questions outlined above, a change of perspective from "what are the effects" to "what is it, that might cause effects" and the analysis and characterisation of nanotechnology, is advisable.

The characterisation of a technology does not only offer indications for positive and negative future effects, it may also serve as the starting point for the analysis of already emerging contexts of application. After all, innovations do not come into being by nature's plan alone but are consciously and unconsciously shaped within innovation systems. The possibility of shaping emerging technologies within innovation systems has to be successfully used. Formulating and applying guiding principles such as "sustainable nanotechnology" is an example of such shaping technology. In order to do justice to the complexity of the chosen task, a three-stage approach for prospective technology assessment and shaping has been developed.

[1] The Institute for Ecological Economy Research conducted the research project "Sustainability effects through production and application of nanotechnological products" in co-operation with the University of Bremen and two business partners. Funding (FKZ 16I1504) by the German Ministry of Education and Science is gratefully acknowledged.

1. Approach - prospective
Evaluation of nanotechnology and its effects through the characterisation of this technology

2. Approach – process monitoring
Evaluation of sustainability effects in concrete nanotechnology applications in comparison to existing products and processes.

3. Approach – constructive
Using guiding principles as influential guidelines within technology shaping, considering short and long term perspective.

1.2. Stage one: Characterisation of Nanotechnology

Every form of prospective technology assessment has to cope with difficulties in predicting effects, the different degrees of the unknown (i.e. the not yet known and the unknowable) and uncertainty. The prospective approach is to focus on the evaluation of a technology by looking at the characteristics of a technology (for details, see Gleich 2004). If the issues of what can and cannot be known at a certain point in time are integrated into the characterisation of a technology in a consequential and reflective manner, the characterisation will give indications of potential hazards and positive effects.

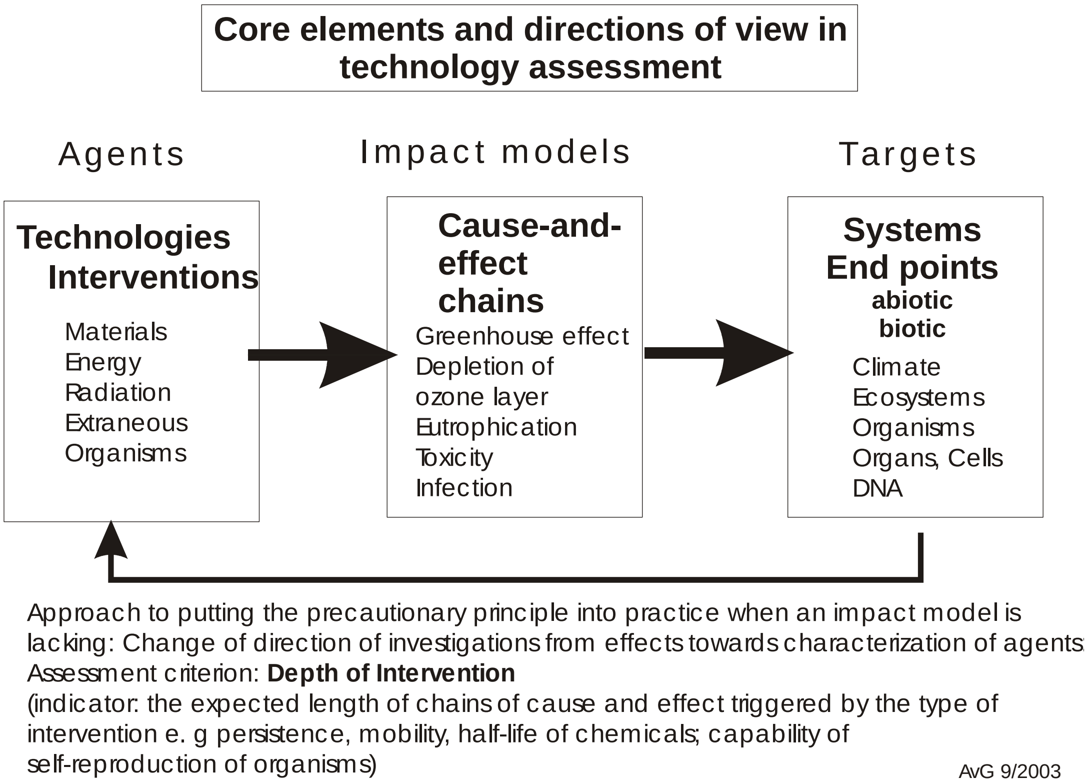
Knowing about the impact of a technology (i.e. the central prerequisite for technology assessment) requires a familiarity with three basic elements:

1) An agent (the technology, substance etc. whose possible effects are to be assessed);

2) An impact model (i.e. a scientifically verifiable theory on how the agent acts on a potential target. Examples include: the greenhouse effect; skin cancer resulting from stratospheric ozone depletion; carcinogenic, mutagenic or toxic effects on reproduction (CMR);

3) A target entity upon which the agent acts (e.g. climate, ecosystem, organism, or organ).

Figure 1: Core elements of technology assessment



Source: von Gleich 2003

It is possible for all three elements to possess unknown qualities. In the case of Nanotechnology, the areas for future applications are for the most part still unknown. Furthermore, Nanotechnology is expected to have an enormous potential for innovation because it may create effects which have not yet been feasible with any other technology.

Nanotechnology is primarily characterised by its overall dimension: the nanoworld. The nanoworld exists at the level of single molecules and atoms the size of a millionth of a millimetre. The specific characteristics of this dimension are that nano-particles show a completely different behaviour to their larger, coarser pendants.

The relatively big specific surface of nano-particles usually leads to an increase in their chemical reactivity and catalytic activity. The relatively small amount of atoms within nano-particles offsets the quasi-continuous solid state of the particle, leading to new, deviating, optical, electrical and magnetic features. From these basic features and characteristics of nanotechnology, a number of possible positive and problematic effects can be derived (see table 1).

Table 1: Nano-qualities and presumed positive ecological including problematic effects

1.1.1.1 Nano-characteristic		+ Positive ecological effects - Problems and potential danger	Approach in assessment
Small size and mobility of particles	+	Concerted use for resource- /eco-efficient technology	Life-cycle-assessment, diffusion- and exposition models, (eco-)toxicological testing animal testing, epidemiology
	-	Entering the lungs and the alveoli Passage of cell membrane and blood-brain barrier Mobility, longevity, solubility as indications for bio-accumulation/ environmental hazards	
Grain-/ layer size, Purity	+	Concerted use for resource- /eco-efficient technology	Life-cycle-assessment, entropy balance, Question of ecological amortisation
	-	Increased production input Higher material- and energy streams, increased resource consumption	
Material quality	+	Possible substitution of harmful and environmentally hazardous substances	Toxicology, eco-toxicology, Ratio between ‚natural' and ‚anthropogenic' material streams
	-	Hazards to human health and the environment through problematic (rare) elements or substance groups in open use	
Adhesion, cohesion, agglomeration	+	‚Intrinsic safety' by tendencies towards adhesion, cohesion and agglomeration?	diffusion- and exposition models, (eco-) toxicological testing animal testing, epidemiology atmospheric chemistry, risk analysis
	-	Behaviour/ fate of emitted nano-particles or fibres in environment, Mobilisation or inclusion of heavy metal toxins by nano-particles	
New chemical effects, changed reactivity and selectivity	+	Use of altered reactivity for resource- and eco-efficient technology. For example utilisation of catalytic effects for more efficient chemical processes or in the environment	Life-cycle-assessment, diffusion- and exposition models, (eco-)toxicological testing also for allergies/ allergization animal testing, epidemiology atmospheric chemistry, risk analysis
	-	Because of changes in solubility, reactivity, selectivity, catalytic and photo catalytic effects, temperature dependency of phase transformation surprising technical, chemo toxic and eco-toxic effects are assumed.	
New physical effects, altered optical, electrical, and magnetic behaviour	+	Concerted use of effects and behaviour for resource- and eco-efficient purposes, e.g. GMR-effect. Tyndall-effect. Quantum effects, tunnel effect	Life-cycle-assessment, For technical systems: FMEA
	-	Mostly depending on highly defined and purified technical conditions, in case of impurities or technical failure surprising behaviour is assumed	
Self organisation	+	Concerted use for resource- and eco-efficient, consistent technology	Risk analysis, depth of intervention

	-	Danger of uncontrollable developments, self-replicating Nanobots	tervention Life-cycle-assessment, environmental impact assessment, scenario techniques

Source: following (Gleich 2004) and (Steinfeldt 2003)

This delineates the potentially dramatic dangers deriving from nano-particles during open use and application of nanotechnology. Possible negative effects off nano-particles, which are of highest priority in current debates about the risks of nanotechnology, have therefore been investigated in a separate case study. If the more futuristic characteristics of nanotechnology are evaluated, aspects of potential self-reproduction become more important.

An example of the ability of a genetically modified organism to self-reproduce opens up a new dimension of risk regarding hazards for human health and the environment. The characteristic of self-organisation should thus prove less problematic. As long as nanotechnology is confined to molecules, the step from self-organising molecules to the self-reproduction of robots or organisms is rather unlikely, as long as it is not actively pursued by science. On the basis of the convergence of nanotechnology with genetic modification of organisms capable of self-reproduction, the creation of self-reproducing mini-robots could, however, be possible.

1.3. Characterising production methods in nanotechnology applications

In addition to the characterisation of nanotechnology, the production methods of relevant nanotechnologies were consequently evaluated. Thus, relevant production methods include Vapour Phase Deposition (CVD, PVD), Flame-Assisted Deposition, Sol-Gel Processes, Precipitation, Molecular imprinting, Lithography and Self-assembled monolayers (SAM). They were evaluated paying attention to the qualitative influences underlying their energy input and the ensuing risk of releasing nano-particles.

Table 2: Evaluating nanotechnological production methods

	Source Material	Method				Product
	Medium	**Facility installation cost**	**Energy input**	**Material conversion** **Material efficiency**	**Potential for release of nano-particle emissions**	**Potential for release of nano-particle emissions**
Vapour Phase Deposition: CVD, PVD	Gaseous	Technically complex procedure Vacuum facility, Strict clean room requirements for clean facilities	**Very high,** due to high fixed energy input (clean room facilities, vacuum) and high energy input depending on vaporisation temperature of source material	**Material conversion: low** Material efficiency: high	Regarding work place: **Very low** because of vacuum technology and closed systems engineering Regarding environment: **Low to medium**, since gaseous by-products can be treated with purification equipment for exhaust air[2]	**Low,** if nanomaterial is encapsulated within a fixed coating **Medium**, if nanomaterial is encapsulated within a coating which is attached to a product **High,** if nanomaterial is produced as powder[3] or tube form
Flame-Assisted Deposition	Gaseous	Rather basic technology, no pre-, or after treatment	**Medium,** since energy is only required for flame (Temp. ca. 1200-2200°C)[4]	**Material conversion: Very high** Material efficiency: high	Regarding work place: **Medium**, emissions through leaks and while filling of nano-particles possible Regarding environment: **Low to medium**, since gaseous by-products can be treated with equipment for exhaust air	**High**, since nanomaterials are produced as nano-particles in bulk and powder form

[2] This evaluation assumes that respective systems for exhaust air are capable of treating gaseous by-products. Whether this is currently technologically feasible is unknown.

[3] (Krämer 2002)

[4] (Rössler et al. 2001)

Sol-Gel Processes	Fluid or dissolved	Rather basic chemical process engineering	**Low**	**Material conversion:** **Middle - high** Material efficiency: high	Regarding workplace: **Low to medium** since process takes place within liquid medium, airborne emissions depend on temperature and vapour pressure of process medium Regarding environment: **Low to Medium**, since discharge of nanomaterial is possible via polluted process media and wastewater. Discharge might be purified with adequate technology[5]	**Low**, if intermediate goods are in liquid form and end products are encapsulated within a fixed layer **Medium**, if nanomaterial is encapsulated within end product, but end product shows no long-term stability
Precipitation	Fluid or dissolved	Rather basic chemical process engineering	**Low**	**Material conversion:** **Middle - high** Material efficiency: high	Regarding workplace: **Low to medium** since process takes place within liquid medium, airborne emissions depend on temperature and vapour pressure of process medium Regarding environment: **Low to Medium**, since discharge of nanomaterial is possible via polluted process media and wastewater. Discharge must be purified with adequate technology.	**Low**, if intermediate goods are in liquid form and end products are encapsulated within a fixed layer **Medium**, if nanomaterial is firmly encapsulated within end product, but end product shows no long term stability

[5] This evaluation assumes that facilities for waste water are capable of treating such fluid emissions. Whether this is currently technologically feasible is unknown.

Molecular imprinting	Liquid	Rather basic chemical process engineering	**Low**	**Material conversion:** **Middle - high** Material efficiency: high	Regarding workplace **Low to medium** since process takes place within liquid medium, airborne emissions depend on temperature and vapour pressure of process medium Regarding environment: **Low to Medium**, since discharge of nanomaterial is possible via polluted process media and sullage. Discharge might be purified with adequate technology.	**Low**, since product features nano structures and no loose particles
Lithography	Solid matter	Technically very complex procedure Technically complex washing and etching processes Strict clean room requirements	**High**, because of high fixed energy input (clean room)	**Material conversion:** **Middle - low** Material efficiency: middle	Regarding work place: **Low to medium**, since the nanomaterials unhinged from solid material exist in liquid medium, airborne emissions depend on temperature and vapour pressure of process medium Regarding environment: **Low to Medium**, since discharge of nanomaterial via polluted process media or waste water possible, may be purified with adequate technology	**Low**, since product features nano structures and no loose particles

Self Assembled Monolayers	Liquid or dissolved	Rather basic chemical process engineering	**low**	**Material conversion:** **Middle - high** Material efficiency: high	Regarding workplace **Low to medium** since process takes place within liquid medium, airborne emissions depend on temperature and vapour pressure of process medium Regarding environment: **Low to Medium**, since discharge of nanomaterial via polluted process media or waste water possible, can be purified with adequate technology	**Low**, if end products are encapsulated within a fixed layer **Medium**, if nanomaterial is encapsulated within end product, but end product shows no long term stability **Medium**, if nanomaterial is encapsulated within a layer which is attached to a product

Production methods taking place in gaseous mediums show a higher potential for the release of nano-particles compared to other methods. This is due to the inclusion of direct emissions at the work place, and they possess loose nano-particles as an end product. The potential for risk is considerably smaller using other production methods if the occurring emissions can be treated with exhaust air – and waste water facilities. Furthermore, process technologies already serving as basic technologies within micro- or opto-electronics require an enormous technical and energy input while resulting in a rather low output.

2. Stage two: Evaluation of application contexts – life cycle assessment

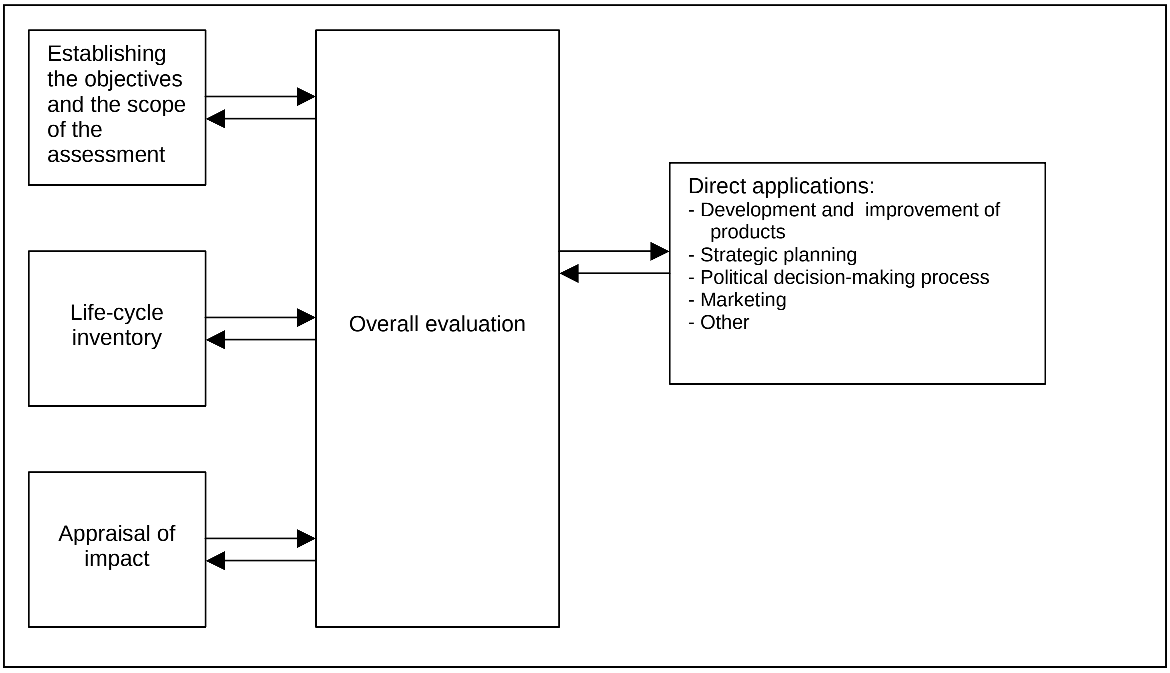
Following on from the characterisation of nanotechnology and the hitherto existing production methods, the second stage of the project was carried out. It aimed at the identification of sustainability effects by process monitoring and evaluation of specific examples of nanotechnology applications. A special focus was given to ecological benefits and risks.

As the focus is on how to predict potential environmental impacts, an appropriate starting point is the method of life-cycle analysis (LCA). This is the most advanced and standardized procedure for evaluating environmental aspects associated with a product and predicting the product-specific environmental impact. Unlike other existing methods, life-cycle analysis offers the possibility of longer-term assessment of eco-efficiency potential.
According to the EN ISO 14040 standard, a life-cycle analysis should consist of the following stages:

- *Establishing the objectives and the scope of the assessment;*
- *Life-cycle inventory;*
- *Appraisal of impact;*
- *Overall evaluation.*

The following flow-chart clearly illustrates interdepence of these steps. The arrows between the individual steps highlight the interative nature of the procedure, with the outcome of a given step always being fed back into the preceding stage and resulting, if necessary, in the repetition of the procedure.

Figure 2: Stages involved in performing a life-cycle analysis



Source: EN ISO 14040 1997

The life-cycle assessment approach also includes methodological deficits: For some of the impact categories there exists no commonly accepted impact model. This is predominantly the case for categories dealing with human toxicity and eco-toxicity.

Moreover, evaluating the exposure to fine dust (the category PM10 risk stands for possible toxic effects through particles smaller then10 μm) within the life cycle assessment method has been regarded as inadequate since nano-particles are much smaller. Life cycle assessment additionally does not consider risks as well as the extent of a possible impact. An extensive set of methods should therefore include well-specified analytical procedures as outlined above .

The weaknesses of the life cycle assessment method have been compensated for within this project by consciously establishing points of focus while selecting the specific application contexts to be researched. Four examples showing a high potential for eco-efficiency were chosen after thorough screening and qualitative evaluation from a whole range of nanotechnological applications. The possible risks and hazards of nanotechnological applications have therefore been analysed and discussed with a detailed focus on nano-particles.

Table 3: Overview of the case studies

Application	Aim
Ecological efficiency of nano-varnishes	Description of ecological efficiency potentials of nano-varnish by elaborating on a comparative ecological profile.
Process innovation within styrol synthesis	Description of potential ecological efficiency for nanotechnology in a catalytic application using a comparative ecological profile Nanotube-catalytic converter compared to an iron-oxide catalytic converter.
Nano-innovations within display sector	Estimation of possible efficiency potentials of energy or resource saving of flat displays (OLED; CNT-FED) through a qualitative comparison with conventional products (OLED - Organic Light Emitter Display and CNT-FED - Carbon Nanotube - Field Emitter Display in comparison to cathode ray indicator tube, liquid crystal display and Plasma display panel)
Nano-applications within lights sector	Description of ecological efficiency potentials regarding energy-saving and long-life white LED's, quantum dots compared to the electric bulb
Open applications of nanotechnology using titanium oxide as an example	Discussion of possible risks and the toxicity potential

2.1. Case study: "The Ecological efficiency of Nano-Varnish"

Our case study **"The Ecological** efficiency of Nano-Varnish" investigates the ecological potential of new, nanotechnology-based coating methods. The coating of aluminium with a new nano-varnish using a sol-gel technology was taken as an example. The evaluation of the ecological benefits was carried out by applying a comparative ecological life-cycle assessment method. The investigation of ecological effects was practically implemented by comparing a nano-based varnish to a water-based varnish, a solvent-based varnish, a powder varnish, and the thus relevant pre-treatments of the surface to be varnished.

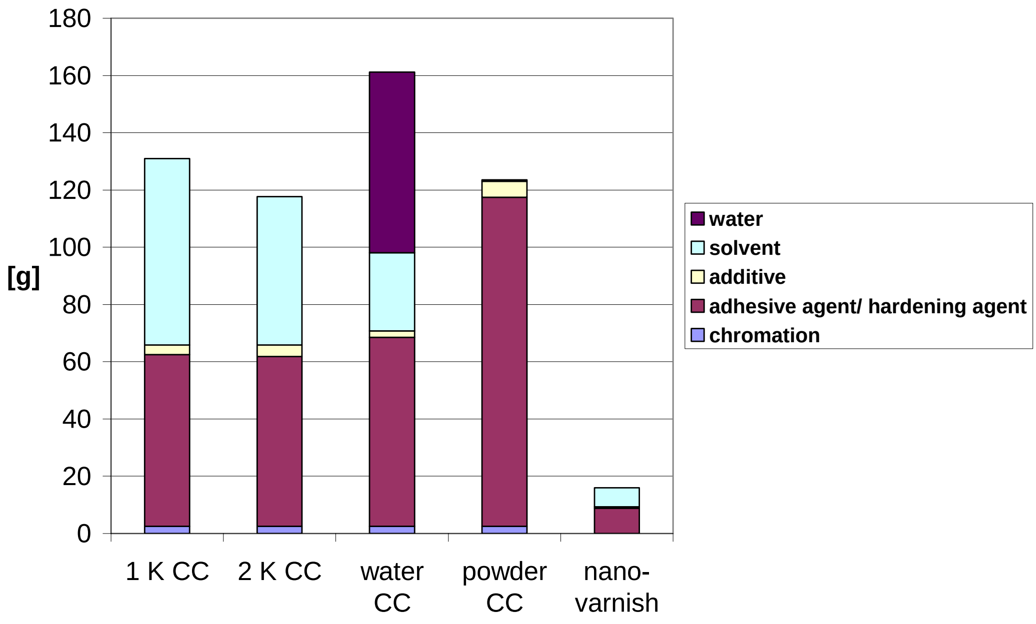
An assessment was carried out for the entire product life cycle of the varnish, including the pre-treatment of the surface. The different life cycle phases are as follows:

- Extraction of raw materials
- Production of basic components adhesive agents, solvents, etc.
- Varnish production
- Pre-treatment of surface
- Varnishing
- Use stage Application phase/ Phase of application
- Disposal/ recycling

We must add that the pre-treatment phase of surfaces could only be considered using a qualitatively evaluation due to missing data. It was hence assumed that the disposal/ recycling phase was identical for all varnishes and therefore not brought into consideration. The most relevant environmental effects are expected to take place within the other life cycle stages.

We could demonstrate by using the examples of nano-varnish, which is already being used commercially, that the application of nanotechnology-based coatings shows a great potential for eco-efficiency in view of emissions and environmental effects. As the same level of functionality is possible using a much lower thickness of the coating layer, a resource efficiency level of the factor five can be obtained.

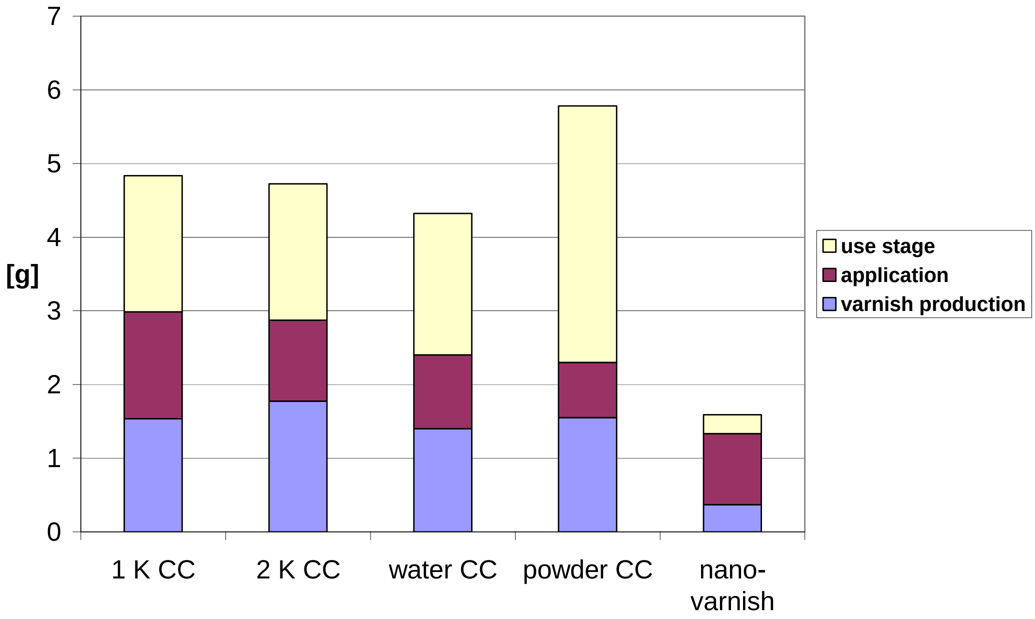
Graph 1: Amount of varnish- and chromation used (g/m² varnished aluminium-car surface)



Source: Harsch und Schuckert (1996) and own presentation

The advantages of using nano-varnishes are visible in VOC-emissions, specifically in the life-cycle stages of varnish production and use phase the application phase. The VOC-emissions of the nano-varnish are thus 65 per cent lower than the emissions of other varnishes.

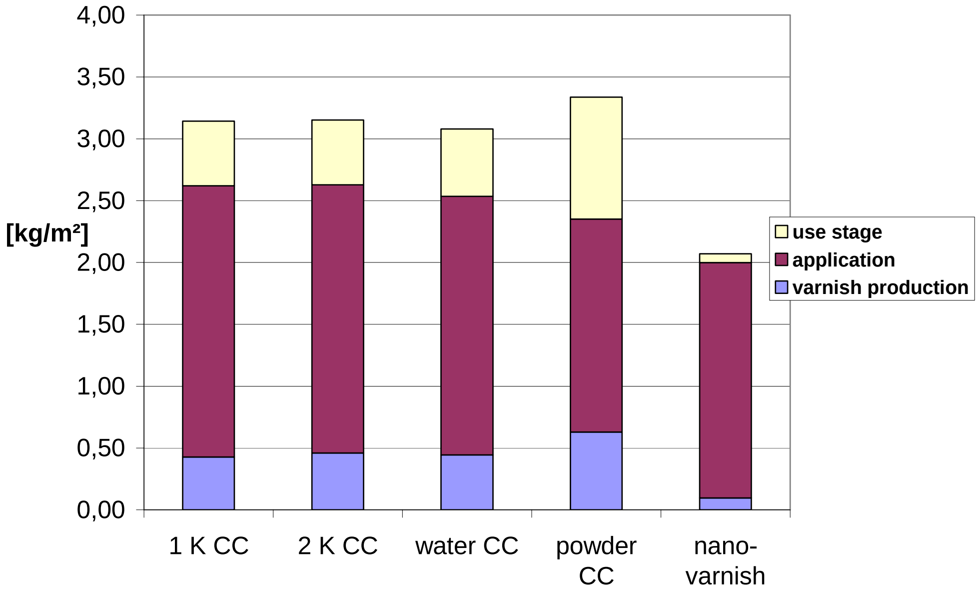
Graph 2: VOC-Emissions (g/m² varnished aluminium-car surface)



Source: Harsch und Schuckert (1996) and own representation

Clear advantages can be established regarding the environmental effects of nano-varnishes. Producing the coatings analysed results in the emission of greenhouse gases carbon dioxide (CO2), methane (CH4) and nitrogen oxide (N2O). The largest component thereby is formed by carbon dioxide emissions caused during the burning of fossil fuels. Similar to the use of primary energy, the nano-varnish causes 30 per cent less greenhouse gases than other coatings.

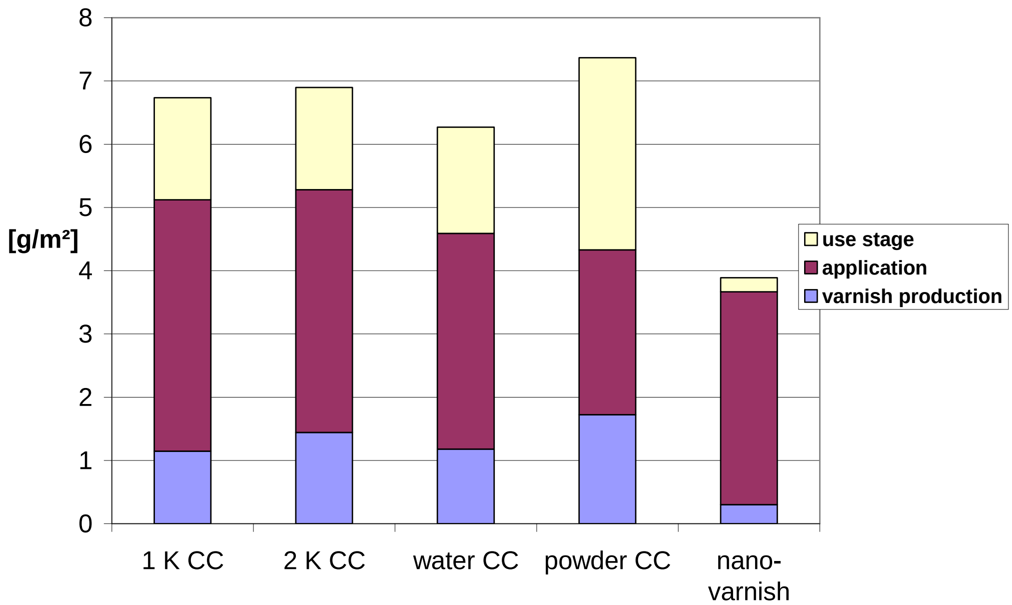
Graph 3: Global warming potential (kg-CO_2 equivalents/m² coated aluminium-car surface)



Source: Harsch und Schuckert (1996) and own representation

Acidification is caused by nitrogen oxide, sulphur oxide, ammonia, hydrochloric acid and fluor carbon emissions. Ammonia, hydrochloric acid and fluor carbon, however, play a less prominent role in the examined scenarios.

Graph 4: Acidification potential (g/m² coated aluminium-car surface)



Source: Harsch und Schuckert (1996) and own representation

Advantages incurred during the use phase application phase are anticipated to be implemented in the transport sector when lightweight construction and -design become more widespread. Thus, environmental advantages could be established within car manufacturing, but would be even higher in the aviation and rail industries.

2.2. Case study: "Process innovation within the styrol synthesis"

Our case study "Process innovation within the styrol synthesis" investigates the potential for environmental relief during catalytic applications. It uses as an example nanostructured catalytic converters based on nanotubes in the chemical process of styrol synthesis.

Since no detailed life-cycle-assessment data for alternative styrol synthesis were available, the level of energy consumption in this process was deducted on the basis of a general outline of the technology.

Table 4: Estimating the energy demand of alternative styrol synthesis

	Classic styrol synthesis	**Alternative styrol synthesis**
Potenial for energy saving		
Change of reactive type from endo-thermic to exothermic		- 1,20 MJ/kg
Reduction of reactive temperature of 200°C, from 600°C to 400°C (25% energy saving)		- 1,59 MJ/kg
Change of reactive medium resulting in a higher selectivity at same rate of conversion (5% energy saving)		- 0,32 MJ/kg
Energy consumption	6,36 MJ/kg	3,25 MJ/kg

The synthesis of styrol using a nanotube catalytic converter reveals the potential of saving 50 per cent of the energy used within conventional procedures at this process level. If this result were to be applied to the entire product life cycle of styrol, this would entail an increase in energy efficiency of eight to nine per cent. In addition, using the new catalytic converter would mean substituting a major source of heavy metals and hence reducing heavy metal emissions during the product life cycle. Potential risks through the application of nanotubes have however to be taken into consideration in view of the benefits described above. Further risks have to be further investigated and have to be considered when developing the corresponding production concepts.

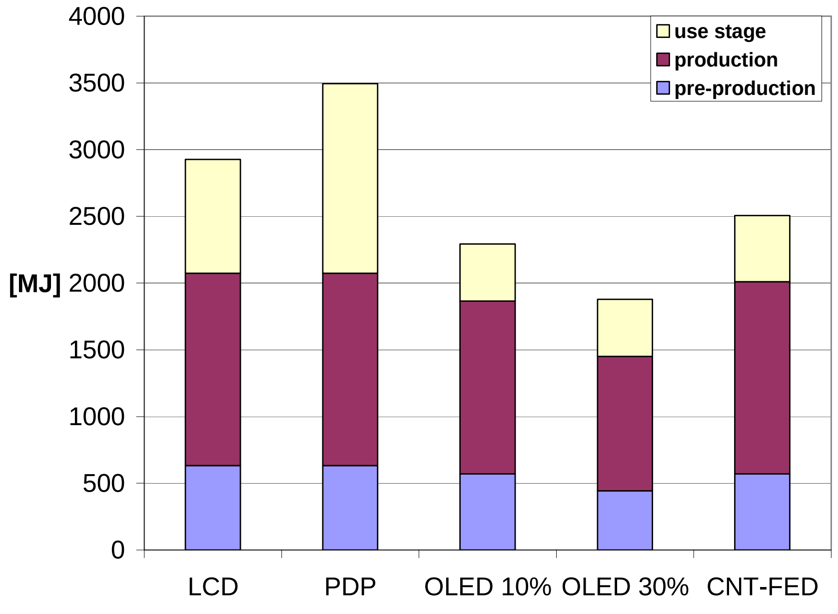
2.3. Case study: "Nano-innovations within the display sector"

The case study "Nano-innovations within the display sector" investigated the potential for eco-efficiency using the application of nanotechnology-based products in the display sector. In order to fulfil this aim, OLEDs and CNT-FED were compared to the conventional displays CRT, LCD and plasma displays. It was more demanding to estimate the potential for eco-efficiency on the basis of the data available than in previous case studies. Many indicators do however point to an increase in material and energy efficiency.

If current problems of long-term stability were to be solved, OLEDs, for example, would stand out for their lower production input requirements. Furthermore, energy efficiency during the use phase is expected to be twice as high compared to conventional LCDs.

On the basis of the described technology, certain assumptions were made for energy use during pre-production and the production phase, to have at least an estimate for future energy use. In this case, various OLED-variants showed different reduction quota because of their simpler structure in comparison to LCDs.

Graph 5: Energy consumption of display technologies within the life-cycle phases.



Source: Socolof et al. (2001) and own calculation

A reduction in energy consumption of up to 20 per cent during the entire life cycle compared to LCDs is indeed feasible. The potential for eco-efficiency is high also for CNT-FED, once developers succeed in designing the highly complex production of nanotubes as equally efficient field emitters. Significant risks using these technologies are, however, not anticipated.

2.4. Case study: “Nanoapplications within the lights sector”

The case study “Nanoapplications within the lights sector” investigates the potential for eco-efficiency in the application of new nanotechnology products within the light sector. For the case study, white LEDs were compared to conventional light bulbs and energy saving light bulbs. Furthermore, the future important potential of quantum dots for this sector was elicited

The most important yardstick for the ecological evaluation of light sources for light~~n~~ing purposes is the energy use in the use phase and the incurred emissions. It was shown that today’s white LEDs offer~~s~~ better results than the classical light bulb, but is three times less efficient than an energy saving lamp. Only when white LEDs reach light efficiency of over 65 lm/W, as it is projected in some scenarios, they will be equally efficient as energy saving lamps and become increasingly relevant for day-to-day light~~n~~ing.

The future practical application of quantum dots will most certainly lead to a further increase in energy efficiency within light sources. Quantum dot technologies are anticipated to find their place in display technology, especially in combination with OLEDs. It will take a few more years, however, until quantum dots reach a position as commercially viable products.

Summarising case studies I to IV

The comparison of the four case studies shows that nanotechnology applications do not automatically hold a potential for immediate environmental relief. At the same time, though, a high level of potential for environmental relief could be shown for most contexts of application. The validity of the established figures of course depends on the quality and availability of material- and energy-related data for the individual applications. Since nano-innovations are still being developed, it is difficult to make precise quantitative claims eco-effects during the production phase. Estimates for the use phase, predominantly regarding the potential for energy saving, are possible, though.

Clearly then, positive statements regarding future potentials for eco-efficiency are visible within a significant amount of areas. Applying the life-cycle-assessment method to currently evolving production processes is a useful instrument of identifying the essential aspects of sustainable technology development.

2.5. Case study: “Risk potentials of nanotechnology application”

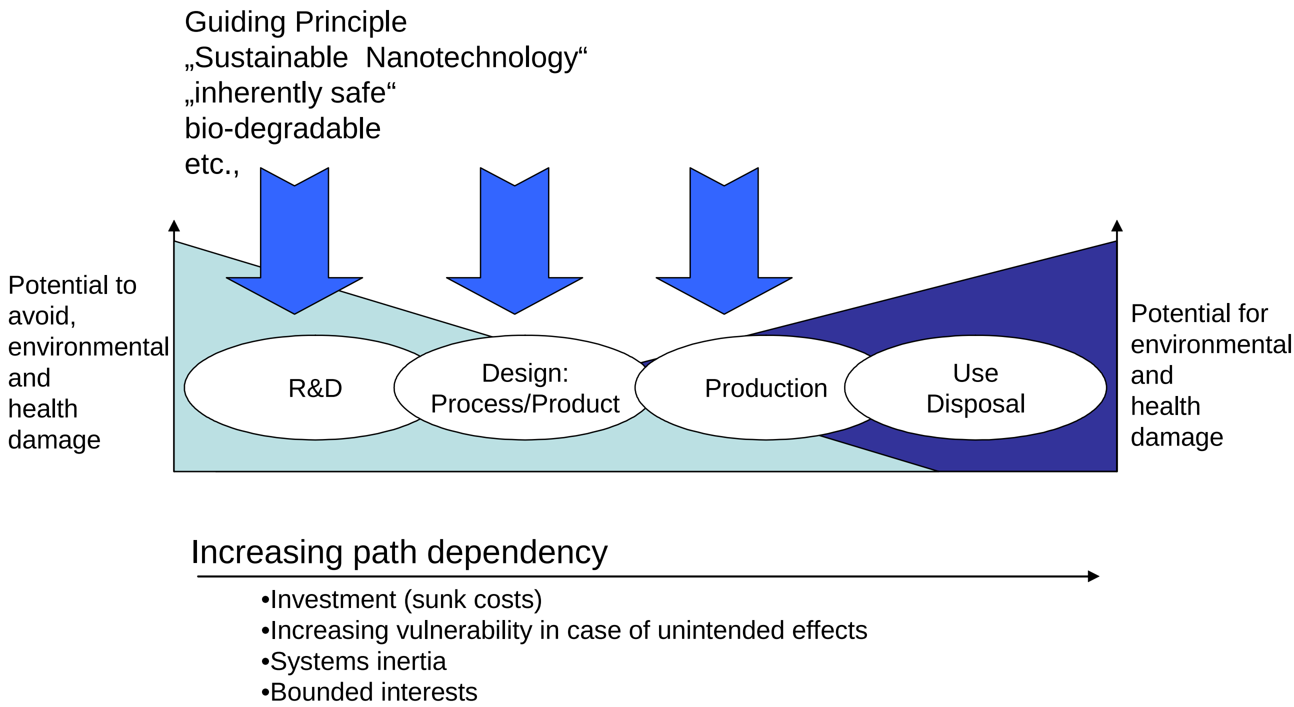
Our case study “Risk potentials of nanotechnology application“ maintained its main focus on the effects and risks of nano-particles. The behaviour of nano-particles differs slightly from particles at the macro-level. Relevant studies at times report somewhat surprising results and indicate toxic effects of nano-particles on the environment and human health. Thus, special importance regarding toxic effects is ascribed to nanotubes and buckyballs. With this in mind, it appears that most scientifically produced knowledge can be said to contain preliminary, inconclusive and contradictory elements and relates merely to a fraction of possible effects.

The applicability of transferring this attained knowledge seems to be however low, and general claims and classifications regarding the toxicity of nano-particles cannot be made at this point in time. There is a great need for further research on the toxicity and influential behaviour of nano-particles on the environment. Considering current methods of production and most applications, the resulting problem of nano-particles is rather small. Methods of production take place mostly in aqueous solutions or within closed systems and nano-particles are therefore tightly encapsulated within a number of products. There are, however, substantial gaps in knowledge regarding the whole product life cycle.

3. Stage three: Technology shaping for sustainable nanotechnology

Technology shaping is only to a limited extent controllable through political intervention. Technology is the result of tangible cooperative action of very different actors leading to the development of a technology path which can be shaped at the same time it evolves. The importance of an early identification of the array of adverse effects on the environment and human health is outlined in detail in figure 3.

Figure 3: Windows of opportunity for technology shaping throughout the life cycle



Quelle: Haum et al. 2004

Figure 3 shows the importance of the R&D stages as well as product design in view of avoiding potentially adverse effects of nanotechnologies. Ideally, a significant amount of the potentially adverse effects should be avoided in the early stages of a product’s life cycle. The knowledge derived from the characterisation of technologies approach may give important leads to the design processes. Bearing this in mind, the design processes should avoid openly tangible problems and make nanotechnologies inherently safe. In this way, problems in the production, use and disposal stages may be avoided. Otherwise adverse effects may be the unavoidable consequence.

The phase in which production processes and products are designed is already partly predetermined because both take place on the basis of already established research and development activities. This phase possesses a relatively strong degree of design and shaping liberties which are crucial to the aspect of intrinsic safety and adverse effects in the subsequent phases. The opportunities for shaping here are more limited than in the preceding phases, but still persist on a substantial level. The chances for technology-shaping will decrease in the production, use, and disposal phases. Within these stages, only additional precautionary and research measures may prevent negative effects on human health and the environment, these usually being connected to high costs.

A technology path is not only shaped by science but also by investment and already established knowledge. Guiding principles should shape these activities in their entity. Guiding principles can thus shape the direction of responsible technological development and contribute to a safe path of development. Thus, three suggestions for guiding principles were made during the project: Resource-efficient nanotechnology, consistent and inherently safe nanotechnology, and nanobionics (more detailed in Gleich 2004).

In addition to these guiding principles as instruments for technology-shaping a number of other approaches to technology shaping have been rectified:

- Sustainable Nanodesign within the research and development phases
- Integration of safety, health and environment aspects into quality management along the value chain.
- Regulatory instruments of the state

Furthermore, additional proposals for new future processes with regard to concepts such as constructive technology assessment and real-time technology assessment were made (Rip et al. 1995, Guston & Sarewitz 2001).

4. Conclusion and suggested measures

The three-stages approach chosen for this project can identify central problem areas by specifying the technology. It has shown significant potential for eco-efficiency in use by applying meaningful life-cycle–assessment. It has also presented extensive approaches for the future shaping of nanotechnology applications. The main conclusions that have been drawn from the research project are:

- Even in the present day, nano-particles in open use represent a significant risk which should not be neglected.
- The results of the life-cycle assessment method demonstrate that significant potentials for eco-efficiency must be exploited, albeit this conclusion ~~is~~ not being valid for the field of application.
- Process monitoring using the life-cycle-assessment method has proven to be an important instrument for technology-shaping based on relevant sustainability criteria.
- It must also be pointed out that technology-shaping approaches using guiding principles play an important role in shaping technology towards future sustainability, inherently because of the results of stages one and two.

In view of the risk evaluation of nanotechnology application, one can observe the need for significant further research regarding:

- Toxicological and eco-toxicological effects
- The behaviour of nano-particles in the environment
- Systematisation of particle-effects
- Integrated research programmes

Further to the applications investigated within the project, which have had a strong preponderance/bias towards inorganic applications, there is a need for increased research regarding

- The potential for eco-efficiency in the field of self-organisation
- Risks within the fields of application of self-organisation such as the effective convergence of nanotechnology with biotechnology and robotics. An important subject therein is the slow transition from self-organisation to self-reproduction

Examining the ecological profiles of nanotechnology applications could be made significantly easier if the relevant data for the individual production processes were made publicly available.

The active moderation of processes within technology development becomes necessary chiefly due to risks established as well as future beneficial methods. If the tremendous economic and social changes currently ascribed to nanotechnology took place, technology development must be accompanied by a more transparent, reflexive, and democratic framework.

Regarding the necessary instruments for accompanying technological processes, we are of the opinion that the standard vehicles of communication (check lists, guidelines, etc.) are sufficient in giving guidance and orientation especially to small and medium enterprises.

- This early phase of technology development offers a vast potential for the effective shaping of nanotechnology towards sustainability. They must be increasingly developed. Shaping by using guiding principle is a very appropriate tool with which to do so.

- Accompanying and shaping oriented processes to be increased (via CTA or real-time TA). Open communication processes are advisable if science, firms and civil society are to be integrated. Also, nanotechnology roadmaps can become a useful instrument for efficient guidance and orientation.

- Accompanying life-cycle-assessment methods should serve as an established means for orientation, and its results should be integrated into shaping technology

- Individual firms have substantial powers within this to shape and design technology, which has to be used in a responsible manner. Integrated management and communication plans have to be developed as to become adequate to the challenges of nanotechnology along the entire value chain. Guidelines in the future have to be developed and tailored specifically to the needs of small and medium enterprises.

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