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Summary

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Environmental Relief Effects through Nanotechnological Processes and Products

Summary

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Environmental Relief Effects through Nanotechnological Processes and Products

The top priority of the research project “Environmental Relief Effects through Nanotechnological Processes and Products” was to identify and quantify, to the extent possible and by means of selected examples, the environmental and sustainability opportunities and risks associated with this rapidly developing line of technology. Environmental relief potentials are understood here to include not only environmental engineering in the narrower sense (end-of-pipe technologies), but also and specifically process, production, and product-integrated environmental protection, thus not least the “input side” on the path to a sustainable economy: the reduction and modification of quantities (resource efficiency) and properties (consistence) of the material and energy flows entering the technosphere.

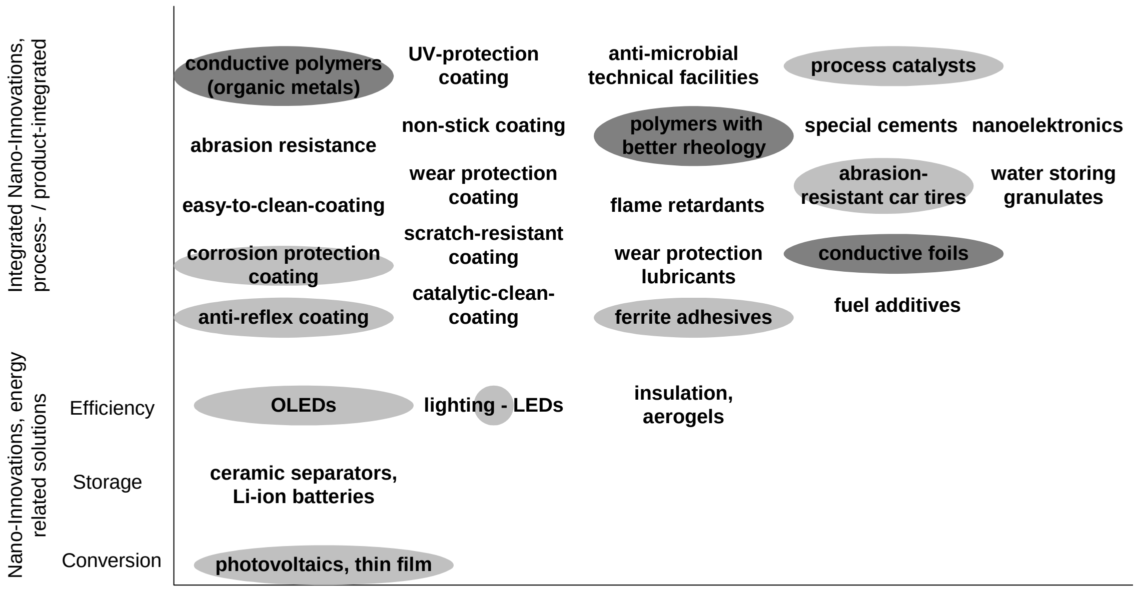
The project consisted of four stages, each making use of a specific method of investigation:

- Analysis of products and processes already on the market or soon to be made available and their application
- Examination and initial qualitative assessment of each of the products and processes with respect to its potential for environmental relief (or burden, as the case may be)
- In-depth life cycle analysis and assessment of four selected processes or products as compared to conventional processes or products
- Supplemental to the environmental assessment, an appraisal of employment potentials for the selected processes and products.

The analysis of new and existing nanotech products and processes with respect to environmental protection/pollution revealed a large and varied number of existing and potential areas of application; however, it must be noted that their environmental relevance has so far only been qualitatively represented. Quantitative investigations of anticipated or still to be realized environmental benefits arising from specific nanotechnical products and processes, as well as further-ranging environmental innovations such as product and production-integrated environmental protection have so far been the exception.

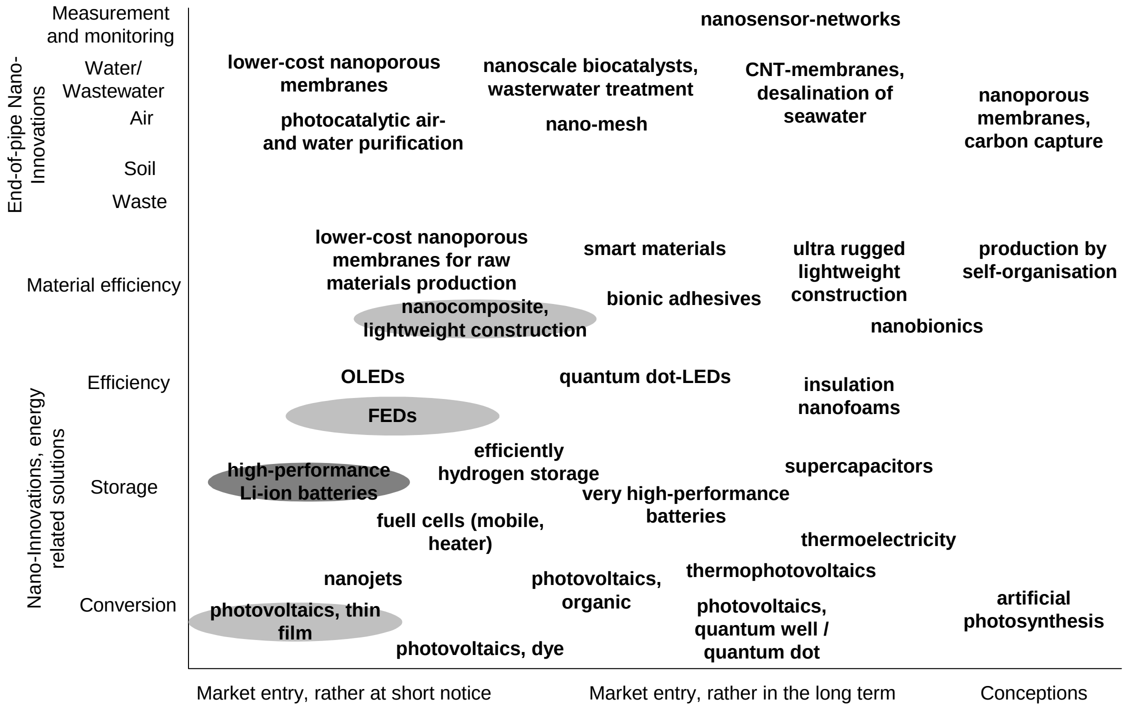
In addition to the potential applications in the area of end-of-pipe technologies, such as membranes (catalysis already extends beyond the purification of exhaust gases in many areas well into the area of integration), the following illustrations make clear that the most predominant and especially far-ranging potentials for nano-environmental innovation are to be found in the areas of integrated innovation and energy. In many fields of application numerous potentials for the realization of environmental benefits are opening up. Those applications for which separate case studies already exist and thus quantitative data with respect to potential environmental benefits are available are indicated below with a light-grey background. The applications with a dark-grey background are those that were chosen for in-depth investigation in this study.

Figure 1: Nanotechnology-based products / applications on the market[1]



[1] Source: authors

Figure 2: Anticipated nanotechnology-based applications[2]



Evaluation of specific application contexts—life cycle assessment

As an assessment approach, the environmental profiles prepared are based on the life cycle assessment methodology. The life cycle assessment (LCA) is the most extensively developed and standardized methodology for assessing environmental aspects and potential product-specific environmental impacts associated with the entire life cycle of a product. It has the advantage that by means of comparative assessments, an (extrapolative) analysis of eco-efficiency potentials 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. 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.

[2] Source: authors

In the following investigations, the focus is placed on the potential environmental relief provided by nanotechnology products and processes. The modelling of individual case studies and their evaluation and analysis according to applicable environmental impacts was carried out by means of the LCA software Umberto. The life cycle impact assessment and evaluation of ecological considerations is based on the partial aggregation method of the Institute of Environmental Sciences (CML) of Leiden University, which allows for the various environmental impacts to be quantitatively ascertained. Risk aspects, particularly in dealing with nanomaterials, are separately addressed in the individual case studies within the framework of a ‘concern analysis’ utilizing relief and concern criteria established by the ‘Risks and Safety Research’ Work Group within the framework of the German NanoCommission, under the direction of the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety. In the form of a preliminary assessment these criteria could be applied in an early stage of technological development, in which (eco)toxicological data are not yet available.

Building on a standardization of environmental innovations, a technology screening was carried out and a group of thirteen proposals for in-depth investigation were drawn up, from which four nanotechnology applications were selected for life cycle impact considerations:

- Manufacture of solderable surface finishes on printed circuit boards by means of nanotechnology, Ormecon GmbH, Ammersbek bei Hamburg
- MW carbon nanotube application for foils in the semiconductor industry, Bayer MaterialScience AG, Leverkusen
- Lithium batteries for energy storage, among others, Litec GmbH, Kamenz
- Ultradur® High Speed plastic, BASF, Ludwigshafen.

The results of the LCA comparisons make clear that nanotech 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—potentials for significant environmental relief could be ascertained using the chosen methods based on a comparative functionality of the different solutions.

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, only limited quantitative data are available. 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.

Printed circuit boards (PCBs) are found in almost all electronic devices, including personal computers, mobile telephones, and televisions, but also in automobiles, airplanes, and satellites. Worldwide approx. 250 million m² of PCB are manufactured each year. In the first case study, the ecological potential of a new nanotechnology-based process for the **manufacture of solderable surface finishes on printed circuit boards** developed by Ormecon GmbH Ammersbek was investigated and compared to various conventional processes. The new OM Nanofinish process is characterized by a combination of new material functionality (organic metal) and its nanoscale nature. As an innovative process for the manufacture of solderable surface finishes on printed circuit boards, OM Nanofinish possesses an enormous potential for environmental relief compared to qualitatively equivalent conventional processes—particularly in comparison to the ENIG, HASL, and immersion processes. The life cycle analysis, based on a comparatively good data pool, clearly demonstrates that the OM Nanofinish performs four to twenty times better than the HASL and immersion processes in all environmental categories. When compared to the ENIG process, this jumps to three digits, for example, in the area of greenhouse gases to a factor of 390. The life cycle assessment data for the OSP process are of the same magnitude as those for the OM Nanofinish, but it must be noted that the fields of application for OSP are not in high-grade production but rather the mass markets and thus only a limited qualitative comparison with the OM Nanofinish process is possible.

Commensurate with the concern analysis that was conducted and in accordance with the knowledge currently available for polyanilin nanoparticles in the application context described (surface finishes for printed circuit boards), it is the view of this study that a minimal level of concern can be assumed.

Current knowledge about the possible environmental impact of carbon nanotubes (CNT) is still quite limited; production to date has been mostly limited to laboratory and research quantities and promising applications still must overcome significant material research challenges. Thus in the case study "**MW Carbon Nanotube Applications for Foils in the Semiconductor Industry**," the decision was made to look at an already existing industrial application. From the start it was clear that in this particular product application the resource efficiency potentials would not be as great as those hoped to be found in future CNT applications, e.g., in the area of new ultra stabile lightweight construction materials. Nonetheless, one goal of the case study was also to fill the current knowledge gap with respect to life cycle assessment data for CNTs. With the cooperation of the firm Bayer MaterialScience AG, it was possible to produce a detailed model of the manufacturing process for multi-walled carbon nanotubes (MWCNT) and to generate specific life cycle assessment data. It was thus possible to make a life cycle assessment comparison with conventional plastic sheets made electrically conductive by adding carbon black. In addition, sensitivity analyses made it possible to identify for more in-depth investigation those parameters having an important influence upon the results.

For all environmental impacts along the life cycle of the new foils with MWCNT, it was possible to establish a positive reduction ranging from a 12.5% for global warming potential to 20% for eutrophication. Polycarbonate, as the main component of the foil so strongly influences environmental impact that manufacturing differences for MWCNT play no role in the individual scenarios. The greatest influence is thus found in increased material efficiency: where before 1000 kg of “old” plasic sheets was required, now only 800 kg of the “new” foil is needed.

With respect to the ‘concern analysis’, one must first address the concerns raised by specific properties of ‘free’ carbon nanotubes. Unaggregated or unagglomerated MWCNTs are presumed to be respirable, are insoluble, and, because of their inert carbon composition, are presumed to have only limited biodegradability. Likewise, the morphology of some nanotubes—in analogy to asbestos or wood dust, both of which have in combination with persistence been determined to be carcinogenic—is also a cause for concern. The fact that MWCNTs are generally found in relatively large agglomerates (in the micrometer range) mitigates this concern certainly, but cannot eliminate it entirely.

Decisive, however, is the question of whether—or more specifically, where—in the product life cycle of the conductive foils an exposure to free CNTs would even be possible. At most this only appears to be possible at the beginning of production of MWCNTs, in the packaging and mixing (formulation) processes, and perhaps at the end of the product life cycle during waste incineration. In the use phase for the user resp. consumer there is thus no immediate cause for concern. In the end, a comprehensive and balanced consideration of what are certainly comparatively minimal advantages in the area of ascertainable LCA environmental relief potentials vs. still unanswered questions in the area of hazard analysis with respect to environmental, health and safety aspects should urge caution.

Alternative power train systems in public transport are currently being intensively researched and investigated, particularly with a view to fuel efficiency and improved environmental compatibility. A tremendous restraint on the deployment of hybrid and pure electric power trains is the lack of suitable solutions to the problem of energy storage. The development of ever more powerful storage units using lithium-ion batteries is one possible solution to these technical challenges, and here, nanotechnology offers some interesting points of departure.

In the course of the third case study, even more prospective in its outlook, a comparative study was carried out of conventional offerings in short-range transit vs. new systems utilizing hybrid power trains—particularly with a view to **environmental relief potentials anticipated from nanotechnology-based further developments in lithium-ion batteries**.

As a result of the investigation but against a background of deductions and assumptions necessary for the LCA comparison, it was possible to establish that the environmental advantages achieved through reductions in fuel consumption by the hybrid system more than offset the additional material expenditures. But only the future variant model demonstrates a difference in environmental impact of more than 20% less than the conventional diesel city bus. On the basis of existing battery technologies as well as those anticipated in the near future, no real breakthrough in environmental efficiency for hybrid power systems in the bus applications examined is presently in sight. Expressed in absolute numbers, over a period of six years a bus based on the future variant model would provide savings of approx. 65 t CO_2 equivalents compared to conventional diesel buses. Even though the additional expense of currently roughly €120,000 per bus can be significantly reduced in series production, there still remain very high specific CO_2 avoidance costs. This must be balanced against the further environmental advantages of the hybrid bus, such as emission-free operation at passenger stops and in the pedestrian zone.

In other applications, nanotech innovations in battery technology—for example, direct electric-drive power trains for motor vehicles—could lead to greater specific environmental relief. In order to better be able to model and make life-cycle assessments of such applications, up-to-date life cycle assessment data for lithium-ion batteries is essential. It certainly would be most welcome if those German firms involved in the development of higher-performance lithium-ion batteries would also do their part to address the issue by making the needed life cycle assessment data publically available in a timely manner.

The case study “**Nanotechnology-based Ultradur® High-Speed Plastic**” looks at the environmental relief potentials of advanced technological plastics, whose working properties have been substantially improved through the selective addition of nanoparticles. Specifically, the rheologically modified engineering plastic Ultradur® High Speed PBT from BASF was selected for investigation and compared across the entire product life cycle with the previous standard PBT. BASF’s own life-cycle analysis served in part as the basis for the case study.

The advantages of this new plastic, with its significantly improved flowability, become particularly evident in injection molding applications. Due to the low melt viscosity, lower injection and holding pressures and a lower processing temperature are sufficient for the realization of equally complex geometries. In the scenario that was studied, a 20% reduction in working time for the same amount of material was ascertained, leading to energy savings of approx. 9% in the injection moulding process. These reductions are also reflected in the other environmental aspects. Only in the environmental impact category stratospheric ozone depletion was a negative impact noted, the origin of which according to BASF is due to the manufacturing process for the organic nanoparticles.

Nanotechnology employment effects

As a result of an investigation of employment effects, based on an appraisal of existing studies as well as a survey that was conducted, it was found that nanotechnology firms have positive expectations for development with respect to their nano-activities—particularly for turnover. The analysis shows that the economic importance of nanotechnology should not be underestimated. In this context, however, it should be noted that nanotechnology can be classified as an “enabling technology” and thus—much as in the material sciences—certainly plays an important role in innovation and economic development, but that ultimately its direct impact upon the creation of new independent “nano-jobs” is very limited. Instead it is much more likely that nanotechnology or the deployment of nanotechnology in the various production methods and products will lead to improvements in the competitiveness of these methods and products, but as a rule this does not involve the creation of new jobs, rather more so the preservation of existing jobs by means of innovative improvements. The further creation of new jobs could then follow with the development of nanotechnology-based processes and products that are so useful that they then lead to the development of new markets.

Conclusions and recommendations for action

In the course of this research project, actual products and processes were analyzed to determine the extent to which the application of nanotechnology can make a contribution to environmental relief. This emphasizes the dimension of opportunities based on nanotechnology. As a result it was found that the application of nanotechnologies in some of the areas of application that were investigated can lead to the achievement of large environmental relief potentials.

At the same time it must be noted that there is no guarantee that processes showing promising results in the prospective life cycle assessment will automatically succeed in the marketplace. Assessment problems are not the only aspect in this connection—many of the processes are still in a rather early stage of development. A key problem is simply that these innovations—as is the case with all forms of innovation—must overcome the forces of inertia—the threat of sunk costs in existing facilities, for example, that hinder the market introduction of new nanotechnology-based processes.

Neither the risks nor the opportunities offered by nanotechnology are a sure thing. The importance of studies such as this one is in demonstrating the potentials that can and must be realized: potentials for the realization of opportunities and potentials for the minimization of risks. Feeding the results of the environmental assessment profiles back into the development process should thus lead to further improvements and optimizations in the design of processes and products; however, investigations of the success of such reinforcing feedback processes do not exist yet and were not possible within the scope of this study.

It could be determined that:

- The concurrent and prospective life cycle assessment has proven itself to be an important instrument in identifying essential elements of sustainable technological development. The systematic provision of life cycle assessment tools and data for the relevant industrially manufactured nanomaterials (CNT, TiO_2, SiO_2, ...) would significantly facilitate further life cycle assessment profiles. The German Federal Environmental Agency, in cooperation with industry, could attempt to strengthen these approaches specifically for these areas and incorporate them into the currently available structures and databases (PROBAS, GEMIS).
- Statements on environmental/sustainability aspects from nanotechnology projects sponsored by the Federal Ministry of Education and Research (BMBF) should be more strongly based on quantifiable evidence with respect to environmental performance and usable life cycle assessment data, which can then be fed back into the public and scientific discourse.
- A quantification of the environmental benefits to Germany provided by nanotechnological processes and products would be helpful not only in federal funding policy, but also and especially for the formulation of the Federal Government’s high-tech, climate, and sustainability strategies. Which contribution nanotechnology can make to overcoming existing bottlenecks, for example, with respect to CO_2 reduction potential or resource efficiency? This should be discussed on the basis of technological road maps, of prospective life cycle assessments and last not least following the example of studies with simplified ecobalance approaches such as the carbon footprint.
- What has been completely lacking so far is an analysis/assessment of the environmental relief potentials offered by particularly far-ranging or even visionary areas of nanotechnology application, such as ultrastable lightweight construction

materials, active nanosystems, and innovations at the interface of nano and biotechnology up to and including artificial photosynthesis and nanobionics.

In the social context, there has been much concern about the establishment of a "safe" corridor for development (conducted by guiding principles as well as guide rails). To assure the greatest possible freedom in the innovation process on the one hand and the implementation of the precautionary principle on the other—and not least with a view to the acceptability and acceptance of very far-ranging innovations based upon nanotechnology. An important initial approach—taking the example of the already ongoing efforts of the German Federal Environmental Agency with respect to the implementation of a guiding principle for a "sustainable chemistry"—would be to likewise initiate and support the development of a new guiding principle: a "green nanotechnology."

It is not possible—or if so, only to a very limited extent—to shape technological development by means of political intervention; rather, it is through the interaction of the various players that a path of development arises that can be constructively influenced by, among other things, the use of a guiding principle as a steering instrument. Since nanotechnology is still principally in an early phase of its development, there still exists in theory at least a large degree of freedom to steer research efforts in the direction of sustainability.

A guiding principle such as "green nanotechnology" or nanobionics could serve as a foundation or starting point. An interesting approach in this direction is found subsequently in the above mentioned criteria of the 'concern analysis', prepared by the Working Group on Risks and Safety Research, within the framework of the German NanoCommission, under the direction of the Federal Ministry for the Environment, Nature Conservation, and Nuclear Safety. At the very least, working from an expanded inversion of the concern criteria it should be possible, at least in part, to also derive 'safety design' criteria for the sustainability-oriented development of nanotechnology-based innovations.