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Green nano: Positive environmental effects through the use of nanotechnology

Summary

The *green nano* design principles developed by the German NanoCommission constitute an attempt to establish consensus-based guidelines for environmentally friendly and sustainable production. This initiative fits into the objective of international research and development policy *(e.g., Responsible Research and Innovation, RRI)* and shall enable to incorporate desired societal aspects into technology developments as soon as possible. The present dossier is concerned with the question to what extent a concept along those lines can contribute to environmentally friendly developments in the area of nanotechnology. For this purpose, it introduces research projects which have implemented certain aspects of the *green nano* design principles. Moreover, on the basis of technological and scientific research and development, the question is raised whether or not, and if so, to what extent concepts such as *green nano* design principles can support the incorporation of environmental aspects into research.

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Introduction

Nanotechnology has long been a focus of risk research. Its effects on life and health (see *inter alia* NanoTrust Dossiers Nos. 019en, 021en, 024en, 033en, 034en) but also on the environment (NanoTrust Dossiers Nos. 005, 012en, 027en, 035en) are continuously studied in order to determine and mitigate possible negative consequences at an early stage. However, there are also areas of application where there is an assumption that nanotechnology can contribute to environmental protection and sustainable production (see NanoTrust Dossier No. 026en). It must be reminded, though, that statements on the environmental and sustainable potential may not be generalized and must therefore be analyzed separately with regard to each type of application in order to assess the environmental potential.[1]

This dossier deals with the topic of nanotechnology and environment on several levels. Firstly, it studies the term *green nano* and introduces different concepts for an environmentally friendly approach. Secondly, it lists specific research and development projects which try to implement *green nano*. Finally, it answers the question whether or not, and if so, to which extent the *green nano* design principles developed by the German NanoCommission have (had) an influence on recent research and development on nanotechnology in the environmental field.

Concepts for responsible technology development

It has often been expressed that the development of new technologies should increasingly be aligned with socially desirable objectives. Concepts such as the EU's *Responsible Research and Innovation (RRI)* shows that societal values and aspirations should be integrated stronger at the political level into the innovation process. Schomberg (2013)[2] provides a (preliminary) definition of *RRI*: "Responsible Research and Innovation is a transparent, interactive process by which societal actors and innovators become mutually responsive to each other with a view to the (ethical) acceptability, sustainability and societal desirability of the innovation process and its marketable products"[3].

However, the idea to intentionally direct technology development into one preferred direction has existed already previously: For example, the so-called "Leitbild approach" enables to specify an overarching objective (*e.g.* sustainability) through combining several guiding principles. These are then further specified and developed by different actors. Thus, in this manner a concept such as *green chemistry* (see below) could contribute to the establishment of more sustainable research and production[4].

The earlier technology development employs mission statements, the better their assumed effects are.[5] In this vein, the mission statement *green nano* should facilitate a more long-term orientation of nano research and development activities.[6] As a framework for sustainable research and development, it has been said to exert a particularly strong influence at the start of the production chain as technology development can be shaped easiest and most fundamentally at this stage. Later on, this is more difficult as further down along the supply chain more and more actors are directly or indirectly involved in the production process. Hence, the notion that nanotechnology is a field where an orientation according to a desired objective (*e.g.* sustainability) is particularly easy to achieve also stems from the fact that it is a relatively young field. The following therefore applies: The earlier there is available knowledge concerning potential effects, the easier it is to formulate guidelines and general conditions.[7]

Environmentally friendly design can be a first step. However, there are certain limits in this regard: Thus, in order to shape processes and technologies in a sustainable manner, conditions of application of products play a major role.[8] While specific intended purposes have certain design requirements, actual effects can hardly be assessed at an early stage.[9]

The term *green nano* in the USA

The term *green nanotechnology* can be interpreted in two ways. On the one hand, a number of general applications and processes can be made environmentally friendlier through the use of nanotechnology (*e.g.* through resource and energy savings, reduction of harmful substances etc.), and on the other hand, the term directly relates to applications in environmental technology.[10] In order to avoid this double meaning, it was differentiated already early on: The Woodrow Wilson Institute[11] used the term *green nanotechnology* in 2007 and contrasted it with the term of *nano-enhanced green technology*. The adaptation of concepts for environmentally friendly production (*green chemistry* and *green technology*) to the conditions of nanotechnology was already considered. Thus, this definition of *green nanotechnology* related particularly to environmentally friendlier production. This was accompanied with *nano-enhanced green technology* as its own point. Box 1 introduces examples of applications for each of the terms.

Box 1: Examples of green nano and green nano-enhanced technologies (Woodrow Wilson Institute)[12]

Examples of *green nano*

- *"Geen nanoelectronics"*
  - Development of new semiconductor material
  - Biomolecular nanolithography
  - Replacement of tin-lead solders with newly developed nanomaterial
- *"Green synthesis of nanomaterials", i.e. environmentally friendlier methods for the production of:*
  - Water-soluble carbon nanotubes
  - Metallic nanorods and nanowires
  - Quantum dots
  - Metal oxides
- *"Green nanomanufacturing"*
  - New methods to fabricate large quantities of organic nanostructures
  - Production of nanofibers made from starches and proteins
  - Development of methodologies and tools for safe nanomanufacturing

Nano-enhanced green technologies

- *Nano-enhanced energy technologies*
  - Development of new kinds of solar cells through semiconducting nanocrystals or flexible solar cells
  - Fuel cells
  - New methods for the storage of hydrogen
- *Nano-enhanced clean-up technologies*
  - Removal of arsenic through magnetic nanoparticles
  - Degradation of heavy metals and organic solvents in water and sediments through zero-valent nanoparticles of iron
  - Detection of hazardous materials in aquatic environments through polymer nanospheres
- *Nano-enhanced "green" industry technologies*
  - Environmentally friendly catalysis made out of mesoporous silica nanoparticles
  - Removal of toxic heavy metals from wastewater through nanoporous sorbent[13]

Box 2: The principles of green chemistry

Green chemistry[16]

- Prevent waste during chemical syntheses
- Design less hazardous chemical syntheses
- Use and generate substances with little or no toxicity to either humans or the environment
- Use renewable resources (e.g. made out of agricultural products or the wastes of other processes)
- Minimize waste by using catalytic reactions
- Avoid chemical derivatives: Avoid using blocking or protecting groups or any temporary modifications if possible. Derivatives use additional reagents and generate waste
- Maximize atom economy: Design syntheses so that the final product contains the maximum proportion of the starting materials
- Avoid using solvents where possible and design safer reaction conditions by using safer chemicals
- Increase energy efficiency by running chemical reactions at room temperature and pressure
- Design chemicals and products to degrade after use
- Analyze in real time to prevent pollution and minimize or eliminate the formation of byproducts
- Minimize the potential for accidents (explosions, fires, releases to the environment etc.) through intentional design of chemicals

Predecessors to the *green nano* design principles

In an attempt to specify the term *green nano* within one exhaustive concept and to summarize its partial aspects, the second German NanoCommission (2009-2011) turned to the already existing list of demands of the US Environmental Protection Agency (EPA) who had already in 2006 defined possible aspects of a more sustainable, greener chemistry and technology.

They understand *green chemistry* (Box 2) to encompass the development of chemical products and processes which reduce or mitigate the use or production of hazardous substances. It can be applied throughout the entire life cycle of a product. While *green chemistry* thereby can contribute to the minimization of pollution directly at the source, it does not rehabilitate environmental damage or contribute to waste treatment (in comparison to *nano-enhanced green technology*).[14] *Green engineering* (Box 3) comprises the design, distribution and use of processes and products. By incorporating this early on into the development of technologies (compare above mentioned Leitbild approach) greatest possible benefits and highest cost efficiency are expected. Developments which fall into this area shall be economic and functional and maintain possible contamination at a minimum.[15]

Box 3:
The principles of green engineering

Green engineering[17]

- Engineer processes and products holistically, use systems analysis, and integrate environmental impact assessment tools
- Conserve and improve natural ecosystems while protecting human health and well-being
- Use life-cycle thinking in all engineering activities
- Ensure that all material and energy inputs and outputs are as inherently safe and benign as possible
- Minimize depletion of natural resources
- Strive to prevent waste
- Develop and apply engineering solutions, while being cognizant of local geography, aspirations, and cultures
- Create engineering solutions beyond current or dominant technologies; improve, innovate, and invent (technologies) to achieve sustainability
- Actively engage communities and stakeholders in development of engineering solutions

Discussions surrounding the *green nano* design principles in Germany

The discussion on the advantages and disadvantages of nanotechnology has undergone several phases.[18] In Germany, the creation of the first German NanoCommission (2006-2008) constituted a change in the debate, shifting the discussion from economic policies to institutions, which were entrusted with the mandate to protect.[19] In the course of this development, there were already first approaches to develop guiding principles for the industry to consider environmental effects. However, they were never implemented.[20] In 2008, the NanoCommission was extended, both with regard to its composition and its orientation. Originally tasked with four thematic groups, an additional Working Group, “Sustainable Nanotechnology – Green Nano”, was created. While the former dealt primarily with regulatory questions[21], the latter analyzed already existing ideas on sustainable nanotechnology and unified these without considering any specific implementation.

Through the adaptation and extension of the *green chemistry* and *green engineering* principles it was attempted to develop a more unified approach to environmentally friendlier production. Unlike the Woodrow Wilson Institute’s definition, the German interpretation understood *green nano* to comprise both environmentally friendly products and production processes as well as improvements of environmental technology. This broad definition of terms is also reflected in the design principles, which can encompass (research) processes and applications.

Box 4:
The German NanoCommission’s green nano design principles (partly abbreviated)[22]

1. **Biomimetics**
   - Use of local materials and energy sources as well as renewable resources
   - Use of molecular self-organization as a manufacturing paradigm (e.g. biomineralisation for the manufacture of hierarchically structured, anisotropic, self-healing substances)
   - Physiological manufacturing conditions (e.g. aqueous synthesis)
2. **Resource efficiency**
   - Atomic efficiency and molecular specificity (e.g. through preventing side reactions, use of enzymatic reactions, precision manufacturing, miniaturization/dematerialization, elimination of cleaning process, and avoidance of rare materials etc.)
   - Energy efficiency (e.g. improving production efficiency (electricity generation, light), reducing process temperatures, lightweight construction etc.)
   - Recyclability (e.g. avoiding losses through using limited range of materials, segregation/modular waste collection, minimizing use of additives and processing aids, avoiding diffuse emissions and contamination of materials)
3. **Minimum risk – benign by design**
   - Avoidance of toxic substances and nanostructures or morphologies which pose a risk to health or safety or to the environment
   - Avoidance of problematic structures, morphologies and hazardous substances (e.g. bioaccumulation, persistence, ability to cross cell membranes)
   - Responsible use of nanofunctionalities[23] (e.g. preference of nanofunctionalities with less risks to human health and safety or to the environment or substitution of hazardous substances by inter alia selection of material and form, coating etc.)
   - Prevention and minimization of potential exposure (e.g. through avoidance of mobility, bioavailability, being bound through a matrix or containment during process)
4. **Energy and environmental technologies**
   - Emissions reduction
   - Environmental monitoring
   - Environmental remediation in and ex situ
   - Switch to renewable materials and energy sources

Green nano design principles

The underlying idea of the design principles is to approximate products and processes as far as possible to natural processes and to create these as safe and environmentally sound as possible. For this purpose, four main areas were identified with varying far-reaching influence on the production process (biomimetics, resource efficiency, minimum risk, energy and environmental technologies), and specified (Box 4). Thereby different points were analyzed where questions of sustainability could either explicitly or implicitly be integrated.

The areas of biomimetics and resource efficiency are reflective of the demand to use little material and energy, and this for as long as possible, at low loss, and for accurate production. For this purpose, natural and simple production processes play a part at every level, *e.g.*, through the use of local material and energy resources or through molecular self-organization.

There is a two-fold approach to potential safety risks for humans or the environment: There shall be as few contact points with nanoproducts as possible; and toxic substances as well as risky nanostructures should be avoided while the use of nanofunctionalities should be responsible.

In comparison, the area of energy and environmental technologies points to new development areas: among the mentioned are resource and energy use, (pollutant) monitoring and emissions reductions as well as new options for improvements of the state of the environment.

The approach of the *green nano* design principles is complementary to regulatory measures. Thus, their application presupposes an already ongoing (public) debate on nanotechnology in addition to a joint feeling of responsibility of all involved actors.[24]

Unlike the Woodrow Wilson Institute, the German *green nano* design principles integrate both general industrial processes and environmental technologies and attempt to take a holistic look at production processes. However, aside from resource and energy procurement, this leaves out local, cultural or (as relevant for planning) social realities which are mentioned in the principles on *green technology*. The main focus is laid on the technical production, whereas other factors which could play a role for the implementation of technological systems are not considered.

Green nano in research: Examples of environmental applications

The following lists exemplary research projects[25] which can be attributed to *green nano*. All projects have an environmentally friendly component, either in the potential context of application, by improving an industrial process, or through the type of technology. As they deal with different aspects of environmental protection, the applied aspects of the design principles also vary (Table 1).

Programmatic terms in concept and application

As shown above, the "green" component is a common topic in all discussed projects, even if the environmental effects vary. Each of these projects falls within one or several points of the *green nano* design principles, *e.g.*, the improvement of environmental monitoring and environmental analytics, environmental restoration, resource efficiency through energy conservation and recyclability.

In the case of ceramic nanofiltration, the main focus was resource efficiency and new technological possibility (such as the application in extreme parameters): At the center of attention are the recyclability of water or other organic solvents as well as a higher energy efficiency of membrane technology in comparison to other methods of separation. This also offers economic advantages (less consumption and therefore less costs of procurement and possibly disposal) while simultaneously aiming at environmental protection (in comparison to other separation procedures).[32]

The dependence of environmental benefits on context is even clearer in the example of sensing technology: While usability and handiness, in addition to improvements in measurement, are primary motives, actual environmental benefits (in disregard of the resource-intensive production[33]) are merely given through the area of application.[34] Hence, the topic of (ecological) sustainability plays an important role in research – on the one hand in the context of its results and in the research objectives, and on the other hand throughout the process of research, *i.e.* the daily research routine. However, this is hardly achieved through abstract concepts but rather through specific requirements in calls for projects or through requirements in industrial applications.[35] On closer examination, it was discovered that researchers partly were aware of the design principles but did not implement them directly.[36] Even if elements thereof were taken into consideration, the *green nano* design principles have so far not established themselves as an action framework for scientific research.

Relevance in the political context

How could such a concept become politically relevant? For one, they evidence the changing debate on nanotechnology: Through the incorporation of a wide spectrum of actors these had the opportunity to bring in their interests at a high policy level in the regulatory debate.[37] In Germany, the discussion was generally consensually-oriented[38], explaining the thematic width and undifferentiated approach of the design principles. At the same time, they are an indicator that informal self-regulatory policy approaches have a differentiated but increasing influence on the political discourse.[39] Approaches like the design principles attempt to answer risk and application-oriented questions and draw connection to societal issues. In this regard, they are in line with the general direction of European research policies, which, for example through *RRI*, push for technological solution in answering to "grand challenges".

Table 1: Overview of environmental aspects dealt with in exemplary projects

Environmentally relevant through ...	Objective/methodology	Name of project	Applied design principles
... the area of application: measuring devices for environmental monitoring	Development of laser-based, more specific measuring devices for pH determination	PLATON	IV. Energy and environmental technologies (environmental monitoring)
.. the improvement of existing industrial processes (conservation of resources)	Development of ceramic nanofiltration membranes to save water and solvents in industrial processes	NANOMEMBRANE	II. Resource conservation: energy efficiency and recyclability
... the restoration of a good state of the environment through new technologies	Rehabilitation of chlorinated hydrocarbon-contaminated locations by introducing iron nano-particles	NAPASAN/ NANOSAN	IV. Energy and environmental technologies (environmental remediation in and ex situ)

Environmentally friendly through the area of application: microelectronics

PLATON – Processing Light: Advanced Technologies for Optical Nanostructures

PLATON developed laser-based measuring devices as a new approach for pH determination. The objective was to avoid inexplicable interferences during measurement and to use new characteristics for the increasing amount of data generated by computers and networks. An additional result was new photonics[26]-based types of measuring devices. The biggest challenge was posed by the growing miniaturization of measuring devices with simplified operation.[27]

The environmental connection of the project follows from its area of application: These measuring devices are used for environmental monitoring and for controlling pollutants and other ecological disruptive factors in industrial waste water. In this manner, developments in the field of microelectronics can contribute to environmental protection and monitoring.

Environmentally friendly through resource conservation: Ceramic nanofiltration

NanoMembrane – Ceramic nanofiltration membranes for sustainable water and solvent conservation by closing cycles

NanoMembrane refined the separation performance of ceramic nanofiltration membranes and tested it for different industrial uses. The focus in this regard was the lower area of separation of nanofiltration as one can find many chemical connections for waste water treatment in that range (e.g. pesticides in agriculture, tensides in industries etc.). In addition, a focus was laid on improving the retention of salts for hardeners (such as, *e.g.*, carbonates and sulphates) and pH stability. By life cycle assessments of waters used in the washing process and the extension of bath lifetimes the membrane shall be used in different industries (*inter alia* textile finishing, metal and chemical) to save water or treat organic solvents.[28]

The use of new filtration techniques protects the environment through water and solvent savings. This enables this applicable to contribute to the sustainability of different industrial process. However, it does not speak to the environment friendliness of the process *per se*.

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Environmental effects and potential benefits on the environment through the use of nanomaterials and -technology without a doubt have a standing in the debate. However, for the integration of sustainability into everyday research there are currently more specific (and therefore more appropriate) means than the design principles. There can be different motivations for internal and external incentives for measures aimed at environmental improvement. This can include such diverse aspects such as research interest, economic benefits of products, or economic advantages in the call for projects. In comparison, the application of the design principles is less effective in pushing "green" technological developments. Nevertheless, a stronger incorporation of this or similar concepts in future could contribute to the creation of a more unified understanding of terms such as "sustainable nanotechnology".

Environmentally friendly through new technologies: Remediation with zero-valent iron nano-particles

NAPASAN – The use of nano-particles for groundwater damage repair[29] & NanoSan[30]

Both projects are concerned with the use of iron nano-particles for the rehabilitation of chlorinated hydrocarbon-contaminated grounds. The primary focus was the improvement of existing procedures with regard to their functionality, applicability and cost reduction. A particularly important aspect concerned the maintenance of the responsiveness of iron nano-particles in order to ensure that the particles could spread over several meters in the subsoil. The NanoSan project embedded particles in a soluble matrix to ensure the affinity of contaminants. Both projects controlled the spread of particles in the subsoil. For this purpose, NAPASAN developed both a measuring coil which enabled to measure the amount of particles per time, as well as a mobile methodology to measure the amount of particles in the groundwater samples. Thereby the reach of the iron-injection could be measured at minimum in the lab and partly also during field research.[31]

Through the use of iron nano-particles also locations which so far could not be treated become reachable. Where damage has already occurred through contamination, this application can contribute to the restoration of a good state of the environment, provided that no adverse long-term effects appear.

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23 Tantamount to nano characteristics: Characteristics of a material which appear if the material is in the nanometer range. The interest in nanomaterials often concerns these characteristics as they are often different from the material's characteristics in another range.

24 See EN 22, p. 4.

25 The selections is merely exemplary and does not intend to constitute an exhaustive project listing.

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