Working Group "Green Nano" 30 August 2010

Aspects of sustainable nanotechnology design
13 design principles

1. Preliminary note

The present draft document sets out the state of developments following the NanoKommission's meeting of 18 June 2010. At that meeting it was proposed that the text should undergo further critical review and, where appropriate, be revised in order to

- avoid sweeping generalisations that could give rise to misinterpretations, and avoid overstating the aspect of learning from nature
- take stock of potential contradictions between requirements arising from different design principles, and emphasise the need to strike a balance.

2. Sustainable nanotechnology design ("Green Nano")

Sustainable development cannot be achieved by means of technical innovation alone, but innovations play an important role in getting there. Nanotechnologies open up interesting opportunities for more sustainable economic development, even though many developments are currently still in their infancy and hence the direction in which these technologies will actually evolve often remains unclear. Hitherto, nanotechnology development has been primarily science and technology-driven. Innovation processes are largely determined by new technological possibilities, especially where these can be linked to solving problems. With an eye to sustainability objectives, the priority at present is to influence science and technology development, in other words to generate a "technology push". The aim of exerting influence in this way is twofold: to steer the development of nanotechnologies in the direction of sustainable applications (e.g. reducing pressures on the environment and protecting resources), but also to foster sustainability in the design of the technologies themselves (Green Nano).

There are few existing examples of potentially feasible ways of involving society at such an early stage of an innovation process. Models of societal participation that involve debating, developing and operationalising a shared paradigm are a rarity. In this paper we discuss one such model, based on the shared paradigm "Sustainable Nanotechnologies", or "Green Nano". The key questions are what a paradigm of this sort would actually look like, and what "design principles" would be needed to implement technology and product design based on it.[1]

The primary target audience for sustainable nanotechnology design, who must receive regular feedback on the design principles proposed here, comprises those engaged in basic research, in research promotion and funding programmes (e.g. the Federal Government's High-Tech Strategy), in strategic corporate development, in company research and development departments, and in stakeholder organisations, especially those concerned with environmental and consumer protection, trade unions and churches/academies (multipliers). In terms of economic players, the focus is

[1] The highly successful "Green Chemistry" initiative in the USA provides a useful model for working with technology paradigms and developing "design principles".

primarily on companies engaged in research, technology developers and manufacturers of nanomaterials. Downstream user industries, particularly system leaders (or key enterprises), such as the automotive industry, are also known to exert considerable influence on upstream developments.

3. Prerequisites

The discussion that follows is based on the current state of developments in the field of nanotechnology. It therefore focuses primarily, although not exclusively, on nanomaterials. Other areas covered include “next-generation” nanotechnologies such as nanosystems (e.g. intelligent drug delivery systems). Additionally, consideration is given not only to elements or systems actually containing nanotechnology, but also to processes and products in which these are used. The entire product life cycle is covered, from sourcing raw materials to recycling.

However, we must begin by pointing out two important prerequisites for working with design principles for sustainable nanotechnology: there must actually be scope for design of this sort in two important areas. Firstly, there must be *scope for action in social terms* within the research and development process. It needs to be possible for participants in innovation systems to adopt the principles and incorporate them into research and development processes. These design principles should not, of course, be (mis)understood as rules. They are goals, or guides for reflection. Tensions are bound to arise between the requirements of different design principles; there may even be contradictions. Using the design principles to implement the overall aims is therefore part of a complex optimisation process. Ultimately, however, these design principles are only one factor among many; technological function and cost-effectiveness are also crucial.

Secondly, there must be *scope for action in technological terms*. The intense interest in nanotechnological innovation on the part of both society and the scientific community is primarily due to nanofunctionalities. By “nanofunctionalities” in this context we mean properties or effects that arise or become more pronounced at the nanoscale. Examples include novel or enhanced optical, magnetic or electrical properties, quantum effects, and nanoparticle reactivity and mobility. Scope for sustainable design exists where nanofunctionalities that make nanotechnology use in a particular innovation process especially advantageous (technical functionalities used in a particular case, e.g. superparamagnetism or quantum effects) are different, and hence functionally distinct, from other nanofunctionalities that are highly problematic for health and safety or for the environment (e.g. particle reactivity or mobility). This will apply in many, but not all instances. Take, for example, a drug delivery system specifically designed to cross biological barriers. In this case it might be counterproductive to try to prevent or minimise this functionality by means of sustainable design. Even here, however, there is potential to prevent or minimise some exposure risks and undesirable side-effects by means of appropriate design or by setting specific conditions of use.

4. Design based on a shared paradigm as a non-regulatory approach to risk management based on the precautionary principle

Shared paradigms can provide orientation in the innovation process. They reduce complexity and provide order. They structure and synchronise the perceptions and shared activities (group identity) of participants in the innovation system. Successful paradigms such as “solar-powered development” and “closed-loop recycling” motivate a great variety of groups. They connect what is desirable (and thereby normativity and emotionality) with what is feasible. This sets them apart from visions and abstract utopias. One of the biggest barriers to innovation is uncertainty concerning opportunities and risks, success or failure; a shared paradigm can help to mitigate these uncertainties.

The design of nano-based processes, products and nanomaterials on the basis of the shared paradigm– as a responsible, voluntary approach to sustainable technology development (as opposed to a regulatory approach) – should be given more attention than in the past. Lest there be any misunderstanding: principles of design are not an alternative to the necessary regulatory risk management measures. They should be seen instead as one element in a broader effort to harness all available means to foster sustainable technology development and risk management based on the precautionary principle.

Dialogue on shared paradigms is a precautionary tool addressing a very early stage of the innovation process, similar to a process of preliminary risk assessment with the aid of criteria for concern and no cause for concern. As the dialogue focuses both on minimising risks and on exploiting potential benefits, it brings together the often separate debates on risks and benefits at the very early stages of innovation. Developing a shared paradigm, moreover, is an approach ideally suited to stakeholder dialogue because paradigms are social constructs that can only come about, and be refined and operationalised, by means of social (public) discourse. Participatory discourse on paradigm development is still embryonic, however, compared to participatory discourse on hazard and risk.

5. Which paradigm? What do “sustainable” and “green” actually mean?

The design principles presented below relate to the goal of developing “sustainable nanotechnologies” (or, in international parlance, “green nano”), by which we mean explicitly taking into account environmental, health and safety considerations.

In other words, they relate essentially to the following requirements for materials, processes and products:

- Closed-loop materials management (recyclable materials and products)
- Resource efficiency (high energy and materials efficiency, atomic efficiency, molecular specificity, low entropy production rate)
- Risk minimisation and adherence to the precautionary principle (low (eco)toxicity, low level of technological risk including explosiveness, radiation)
- Solar-powered development (economic development based on renewable energy sources and replenishable feedstocks).

The paradigm of “sustainable nanotechnologies” encompasses a rather broad spectrum of options, ranging from emissions reduction and environmental remediation measures at one end of the scale to biomimetics at the other. The goal of the latter is not only to minimise and prevent adverse effects (“design for safety”), but also to bring about positive benefits for human health and the environment. A term often used to refer to this is “benign by design”[2]. The metabolic processes of

[2] cf. Anastas 1994

living organisms – the way in which organisms use materials, energy resources, and principles of self-organisation – are fascinating. Many paradigms of sustainable management are in fact realised in the biosphere: low-waste, high-efficiency material conversion processes at ambient temperatures, solar economy, closed-loop material cycles. Looking to nature for models must not, however, be taken to extremes or elevated to the status of dogma. An innovation is not necessarily good simply because it has come about in line with a particular paradigm. There are situations in which paradigms merely increase the likelihood of achieving an intended goal. All innovations, however, including paradigm-based innovations, must ultimately undergo a complex appraisal process using the conventional methods for evaluating technologies, materials and products.

6. How the design principles are organised

The design principles set out below are subdivided into four key areas (see Figure 1):

I. Biomimetics

II. Minimum Risk

III. Resource Efficiency

IV. Energy and Environmental Technologies

The innovation step size would generally be expected to increase incrementally from bottom left to upper right.

Figure 1:
How the design principles are organised

Sustainable nanotechnologies – 13 design principles

Resource Efficiency
- Atomic efficiency and molecular specificity
- Energy efficiency across life cycle
- Recyclability

Energy and Environmental Technologies
- Emissions reduction
- Environmental monitoring
- Environmental remediation
- Switch to renewable materials and energy sources

Biomimetics
- Use of local materials and energy sources
- Self-organisation as a manufacturing paradigm
- Physiological manufacturing conditions

Minimum Risk
Prevention/minimisation of:
- toxic substances and nanostructures or morphologies which pose a risk to human health or safety or to the environment
- nanofunctionalities which pose a risk to human health or safety or to the environment
- potential exposure

7. Design principles – the details

I. Biomimetics

1. Use of local materials and energy sources ("opportunistic" approach to energy and resources)
Priority is given to renewable and locally available sources of energy and replenishable resources, and materials already circulating in substantial quantities in biogeochemical cycles.
Examples: solar power, waste heat, naturally occurring biogenic materials (e.g. cellulose, plant oils, etc.), limestone, etc.

2. Self-organisation (bottom-up) as a manufacturing paradigm

Priority is given to using molecular self-organisation and process environment manipulation in the manufacture of complex structures and systems.

Examples: Self assembly (e.g. self-assembled monolayers, or SAMs), template-induced crystallisation (biomineralisation) for the manufacture of hierarchically structured, anisotropic, self-healing active substances.

3. Physiological manufacturing conditions

Priority is given to "physiological" manufacturing and processing conditions.

Physiological manufacturing conditions: one example of near-physiological conditions is "aqueous synthesis", using a pH of around 7, ambient pressure and temperature, and reduction or, if possible, complete elimination of hazardous substances.

II. Minimum risk – "benign by design"

4. Avoiding toxic substances and nanostructures or morphologies which pose a risk to health or safety or to the environment

Priority is given to low-risk design ("benign by design"). Problematic nanostructures, nanomorphologies and hazardous substances are avoided.

Examples of problematic morphologies and properties: similarity to asbestos.
Examples of hazardous properties: ability to bioaccumulate, persistence, toxicity (to the environment), ability to cross cell membranes, cell reactivity, dust-generating/explosive capacity.
Possible basis for "benign design": Quantitative Structure Activity Relations (QSAR).

5. Responsible use of nanofunctionalities

Intentionally manufactured nanofunctionalities are used in such a way as to minimise nanofunctionalities associated with *risks to human health and safety or to the environment* and/or in such a way as to prevent or minimise existing technological or substance-related risks (substitution of hazardous substances).

Examples of problematic nanofunctionalities and surface properties of nanomaterials: ability to cross biological barriers, mobility in environmental media, reactivity.
Ways of eliminating /minimising/preventing problematic nanofunctionalities: selection of material and form, coating, surface functionalisation using ligands, etc.
Nanotechnologies offer interesting potential for substituting hazardous substances in e.g. solvents, flame retardants, metals, etc.

6. Minimising and, wherever possible, preventing potential exposure

Nano-objects and systems, processes, products and product life cycles are designed in such a way as to minimise potential emissions and exposure, and where possible prevent them altogether.

Ways of minimising/preventing exposure include ensuring that objects and materials are designed to minimise mobility and bioavailability, or are bound within a matrix. Exposure minimisation/ prevention can also be incorporated into process and product design at a variety of levels – e.g. by means of containment, and not least by reducing the amount used in the manufacturing process or product to the lowest possible level. In addition to the other principles, further important considerations include preventing release of nanomaterials for which we have no biopersistence information, and preventing materials from being placed on the market unless methods are available for reliably identifying the substance in the body/in the environment and for determining on-site exposure.

III. Resource efficiency

7. Atomic efficiency and molecular specificity

Manufacturing and processing are designed in such a way as to minimise waste generation and material intensity.

Ways of achieving molecular specificity and atomic efficiency and preventing/minimising side reactions, waste and emissions include molecular recognition processes, (auto)catalysis, enzymatic reactions and precision manufacturing and design.

Ways of ensuring low material intensity include miniaturisation/dematerialisation, eliminating laborious cleaning processes in manufacturing, avoiding use of rare materials (which have a large “ecological rucksack”), economising on cleaning materials by using self-cleaning surfaces, and preventing dissipative losses, e.g. by corrosion control.

8. Energy efficiency

Processes and products are designed with a high degree of efficiency, including energy efficiency, across the whole of the product life cycle.

Ways of enhancing energy efficiency include e.g. improving production efficiency (electricity generation, light), reducing process temperatures, minimising entropy production (conversion to heat and heat losses), using lightweight construction, etc.

9. Recyclability

Materials and design processes and products are selected to ensure that materials can be recycled without significantly compromising quality in the technosphere. Irreversible (dissipative) losses are avoided/minimised.

Ways of improving recyclability: using a limited range of materials, segregation/modular waste collection, minimising use of additives and processing aids, avoiding dissipative uses, diffuse emissions and contamination of materials (impurities).

One “nano-option” that is particularly promising, for example, involves producing a material of various qualities (including anisotropic) by deliberately influencing the crystallisation (nucleation) or polymerisation process instead of using alloys and additives.

IV. Energy and environmental technologies

10. Emissions reduction

Opportunities provided by nanotechnologies are used to reduce emissions.

Nanotechnology-based ways of reducing emissions include most notably filters, membranes, precipitants and catalysts (off-site, on-site), and also nanoelectronics for process monitoring and process management in the industrial context.

11. Environmental monitoring

Opportunities provided by nanotechnologies are used for environmental monitoring.

Nanosensors and nano assays provide potential for enhancing environmental monitoring.

12. Environmental remediation

Opportunities provided by nanotechnologies are used responsibly for on-site and off-site environmental (soil, groundwater) remediation.

Taking into account the other principles, approaches here include for example off-site use of iron nanoparticles for catalytic decomposition at sites contaminated by petrochemicals, or for arsenic adsorption in the context of drinking water supply.

13. Switching to renewable resources and energies

Renewable sources of energy and sustainable resources are used.

Taking into account all the other principles here too, nanotechnologies have potential applications in the context of wind power, solar thermal energy, biomass conversion, etc.

8. Limits of sustainable design

At present, most innovations in the nanotechnology field remain predominantly technology-driven. Innovation processes are largely determined by new technological possibilities. Moreover, many innovation processes are still at an embryonic stage of development. The design principles outlined above relate primarily to this embryonic stage and to the technological functionalities that are the focus at this stage. This of course limits their scope just as much as the fact that very little is known at present about the potential benefits and risks of a given innovation.

Ultimately, however, the potential benefits and risks of nanotechnology-based innovations will not be determined by technology alone. The applications, operating conditions and contexts in which they are used are at least as important in this regard. The more the effects of materials, processes and products are determined by the purpose and context in which they are used, the greater the need for additional design principles relating specifically to those purposes and contexts.

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