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Nanotechnology development in Denmark - Environmental opportunities and risk

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Nanotechnology development in Denmark - environmental opportunities and risk

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Abstract (max. 2000 char.):

The present report represents the nanostudy part of a larger study entitled "Green Technology Foresight about Environmentally Friendly Products and Materials – Challenges from Nanotechnology, Biotechnology and ICT" (Jørgensen et al. 2006).

The study was made for the Danish Environmental Protection Agency and feeds into recent international trends in developing a stronger innovation perspective to environmental policy, noticeably the EU ETAP (European Environmental technology action plan) process. In Denmark it is related to the development of a Danish environmental technology action plan (forthcoming in summer 2006).

The analysis focuses not only on the environmental impact but even more on the dynamics involved in nanotechnology development of which we currently know very little.

Applying an innovation economic perspective focus is placed on analysing *the direction* of the nano search and technology development processes and how environmental issues enter into these. Hereby, the future trajectories of nanotechnology development is sought captured, indicating likely long-term perspectives of the Danish nanotechnology development.

The content of the report is as follows:

- What is nanotechnology? Definitions and dynamics.
- What do international findings say on environmental opportunities and risks of nanotechnology?
- The path creation processes within nanotechnology in Denmark. Focus is on how environmental issues enter into the strategies and search processes of Danish nano researchers and related industry.
- The identification of nanotechnology eco-opportunities more generally and through 6 short case studies.

A very wide range of nano eco-opportunities have been identified although most of thse are at a very early and highly uncertain stage of development. Generally, however, green attention and search rules among Danish nanoresearchers are quite weak, meaning that many eco-opportunities are likely to be neglected and environmental and health risks overlooked.

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Preface

The present report represents the nanostudy part of a larger study entitled "Green Technology Foresight about Environmentally Friendly Products and Materials – Challenges from Nanotechnology, Biotechnology and ICT" (Jørgensen et al. 2006). The objectives of the project have been:

- to analyse the environmental potentials and risks in general and in relation to chemicals in particular, related to nanotechnology within the coming 15 – 20 years.
- to identify areas, where Denmark has or could achieve eco-innovation potentials based on nanotechnology.
- to analyse how environmentally promising innovation paths might be supported in Denmark and in the EU, and develop policy recommendations for integrating environmental and innovation efforts.

The project has been financed by the Danish Environmental Protection Agency and has run from February 2004 to June 2005. It feeds into recent international trends in developing a stronger innovation perspective to environmental policy, noticeably the EU ETAP (European Environmental technology action plan) process. In Denmark it is related to the development of a Danish environmental technology action plan (forthcoming in summer 2006).

The foresight study has been carried out by a consortium comprising: Department of Manufacturing Engineering and Management at the Technical University of Denmark (DTU), the System Analysis Department at Risø National Laboratory and Institute for Product Development, DTU have been responsible for the project under the joint leadership of Michael Søegaard Jørgensen, DTU and Maj Munch Andersen, Risø. Maj Munch Andersen has been responsible for carrying out the nano analysis with contributions from Birgitte Rasmussen, Risø. Stig Olsen, IPU at DTU, has contributed with environmental assessments on 6 nano cases.

1 Introduction

Few technologies have attracted so much attention and funding internationally as nanotechnology (Luther 2004b). Interestingly, environmental issues play an usual large role in the debate of this emerging general purpose technology. Especially risks and ethical issues are gaining increased attention. A hypothesis could be that risks and ethical issues will be as important or more to nanotechnology development as they have been to the development and market acceptance of biotechnology. New regulations are being considered and a series of research projects are either emerging or are under way around the globe, notably the recent report from the Royal Academy (2004) and EC SANCO (2004). These reports have presented some of the most comprehensive research so far on the toxicity of nanotechnology, expressing serious concerns related to nanoparticles.

Nano eco-opportunities are very often referred to in the futuristic literature outlining the scope of nanotechnology which dominates much nano writing hitherto, (but seldom in the risk or technology assessment literature), often with very high expectations for considerable environmental advantages (Jacobstein 2001;Wood et al. 2003; Nanoforum 2004; The Royal Society 2003, 2004; European Commission 2004). However, since these statements are often of a very general and superficial character, more in-depth studies are needed. Not only on the scope but even more on the dynamics involved of which we currently know little.

The intention of this study is particularly to add to the latter. The purpose is twofold:

- It seeks to investigate the dynamics of early *path creation* within nanotechnology; more specifically how environmental issues form a part of the search processes of the various actors in the emerging nano technological field in Denmark. This is in other words a qualitative analysis of the drivers, expectations and learning modes among key nano actors in the Danish innovation system.
- It aims to identify (map) the eco-opportunities and eco-risks related to nanotechnology as perceived by the Danish nano researchers.

It implies in other words a broad scanning, which naturally limits the depth of the analysis of specific scientific and technology developments as well as their environmental implications. On the other hand, it offers an opportunity to give a comprehensive picture of where the main innovation activities and search processes in the Danish nano community seem to be heading and which actors (researchers and companies) are involved. The mapping, then, provides the broader context in which the individual innovations should be seen.

The mapping also aims at facilitating networking in the emerging Danish nano community, both during and after the foresight project. Such a mapping of research activities in the Danish nano community has not been carried out previously.

This analysis does not seek to discuss how green nanotechnology is or where the best eco-opportunities are. This task makes little sense owing to the very early stage of development and the highly diverse nature of nanotechnology. Nanotechnology is currently too immature, diffuse and big really to corner the effects. Since it is hardly a technology yet, the uncertainties about future developments are considerable. The analysis here focuses rather on analysing *the direction* of the nano search and technology development processes and how environmental issues enter into these.

Applying an innovation economic perspective focus is placed on early path creation and identifying the expectations for eco-opportunities and risks related to nanoscience. By analysing path creation, the evolving lock-in into technological paths is highlighted. Hereby, the future directions of nanotechnology development is sought captured, indicating likely long-term perspectives of the Danish nanotechnology development.

Very few such innovation studies at the microlevel of nanotechnology development have been made so far in Denmark or elsewhere, so there are few data and analyses to build on or relate to. The current analysis should therefore be seen as early, speculative findings in need of further research. The analysis builds mainly on an interview-based qualitative analysis combined with a broader interactive mail-based survey and mapping exercise undertaking within the Danish nano community.

The content of the report is as follows:

- What is nanotechnology? Definitions and dynamics.
- What do international findings say on environmental opportunities and risks of nanotechnology?
- The path creation processes within nanotechnology in Denmark. Focus is on how environmental issues enter into the strategies and search processes of Danish nano researchers and related industry.
- The identification of nanotechnology eco-opportunities more generally and through 6 short case studies.

2 Nanotechnology – definitions and dynamics

This section seeks to present and characterize nanotechnology. A few comments are made on the innovation dynamics of nanotechnology and how innovation in nanotechnology is analysed in this report.

2.1 What is nanotechnology?

Nanotechnology is an emerging general purpose technology. It is expected to have widespread impacts on society by replacing or influencing existing materials and technologies. The scope of nanotechnology is as yet very uncertain, but some anticipate that it may form the basis of a new industrial revolution, i.e. disrupt and transform the existing technology platforms in the same way as the steam engine, electrification and computer technology.

Nanotechnology is commonly understood as dealing with very small things. A nanometer (nm) is indeed small, one thousand millionth of a metre. The significance of the nanoscale, however, is not only that things are small, but that materials obtain new properties at this scale. This is mainly due to two factors. First, nano materials have a relatively larger surface area. This can make materials more chemically reactive and affect their strength and electrical properties. Second, quantum effects can begin to dominate the behaviour particularly at the lower end of the nanoscale. This affects the optical, electrical and magnetic behaviour of materials.

Materials can be produced that are nanoscale in one dimension, such as very thin surface coatings; or two dimensions such as nanowires and nanotubes; or in three dimensions such as various kinds of nanoparticles.

Nanotechnology is the design, characterization, production and application of structures, devices and systems that entail controlling the shape and size at the nanometre scale.

The size range of nanotechnology is often delimited to 100 nm down to the molecular level (approximately 0.2 nm) because this is where materials have significantly different properties. But how strictly to delimit nanotechnology is a matter of dispute. The need to integrate with other length scales to obtain wider technology development is emphasized.

Nanoscience is the study of phenomena of materials at atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.

Since the 1990s the term nanotechnology has shot into the limelight; However, research into and even technologies based on nanoscale structures is nothing new.

What has led to a breakthrough and hence the rise of nanotechnology as a phenomenon is the development of new sophisticated tools to observe, measure and manipulate processes at the nano-scale level. These tools have emerged within the last 25 years, noteably tools such as STM (scanning tunnelling microscope) from 1982, AFM (atomic force microscope) from 1986, and TEM (transmission electron microscopy), but nowadays there are a range of other tools. Before these tools emerged, research and development at the nanoscale was based on experimental trial and error.

The new tools are leading to a greater understanding and control of processes at the nano scale, and gradually the ability to design materials with specific properties. Research using and manufacture based on these instruments is currently what constitutes the nanotechnological field. “Nanometrology”, research into standardised ways to measure and characterize materials at the nanoscale, is central for the development of nanotechnology.

Conceptually, the rise of nanotechnology was laid out by the physicist Feynman in his lecture from 1959, “There is plenty of room at the bottom”, where he foresaw the possibility to examine and control matter at the nanoscale. The term nanotechnology was first used by the Japanese researcher Taniguchi in 1974 when he referred to the ability to engineer materials at the nanometre scale. The driver was miniaturization in the electronics industry. Already in the 1970s nanostructures were created as small as 40-70 nm using electron beam lithography.

Today, much nanoresearch and -development is still at the experimental stage (Lux Research 2004; Cientifica 2003). Commercialization of nanotechnology depends on laboratory experiments being turned into large scale, reliable and economic methods. Techniques and specific instrumentation for fabrication, control and measurement at the nanometer scale are under development but face major challenges. Concerning production methods two main routes can be distinguished:

- *Top-down approach:* Reduction in structure sizes of microscopic elements to the nanometer scale by applying specific machining and etching techniques (e.g. lithography, ultraprecise surface figuring)
- *Bottom-up approach:* Controlled assembly of atomic and molecular aggregates into larger systems (e.g. clusters, organic lattices, supramolecular structures and synthesized macromolecules).

Current commercial nanoproducts are based on top-down approaches, while bottom-up approaches are still more - and in some cases very - experimental. It is here, though, that big expectations exist of achieving efficient, large-scale, fast production of nano materials that could form the basis of an industrial revolution. As yet, however, bottom-up manufacturing methods have not really materialized, meaning that the connectivity and future paths of the nano technological field are highly uncertain.

In the most recent years, we are seeing a beginning synthesis of the top-down and bottom-up approaches, a significant stage in the materialization of nanotechnology.

Below some main features of nano production techniques are illustrated.

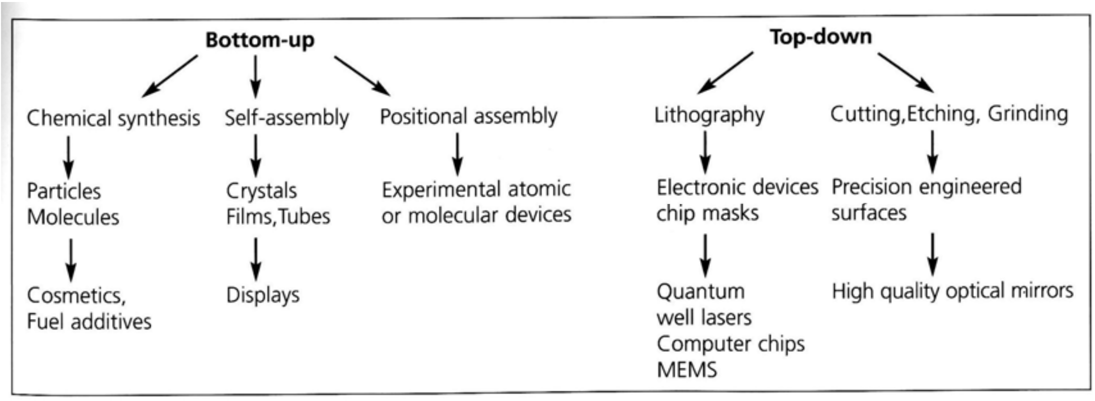

Figure 1. Bottom-up and top-down nano manufacturing techniques (The Royal Society 2004, p. 25)

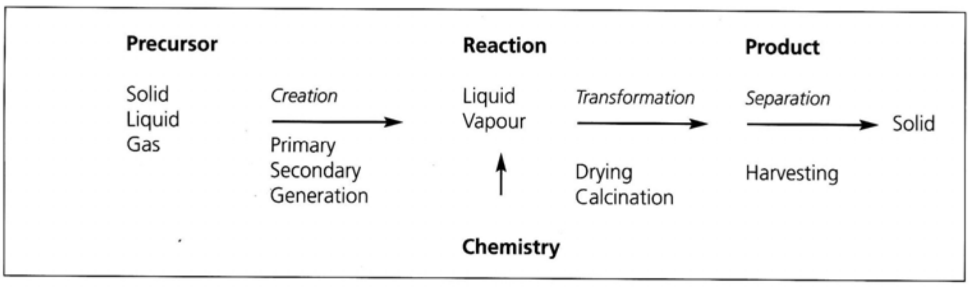

Figure 2. Generic processes in the production of nanoparticles, (The Royal Society 2004, p.25)

In many ways nanotechnology is not yet á technology, and perhaps it never will be. It may better be characterized as a platform technology, rather than one distinctive technology, which entails a wide range of very different fabrication techniques, as Figure 1 illustrates. Indeed, many consequently refer to nanotechnologies in the plural.

Adding to the confusion as to what constitutes nanotechnology is the multi-disciplinarity of the field. Nanotechnology is based on a convergence, during the latest century, of basic disciplines such as technical physics, molecular biology, and chemistry, all trying to operate and manipulate at a nano-scale level, see Figure 3. This common scale of operation and manipulation has opened up for a multi-disciplinarity and combination of scientific paradigms leading to new research areas and possibilities for new technology development.

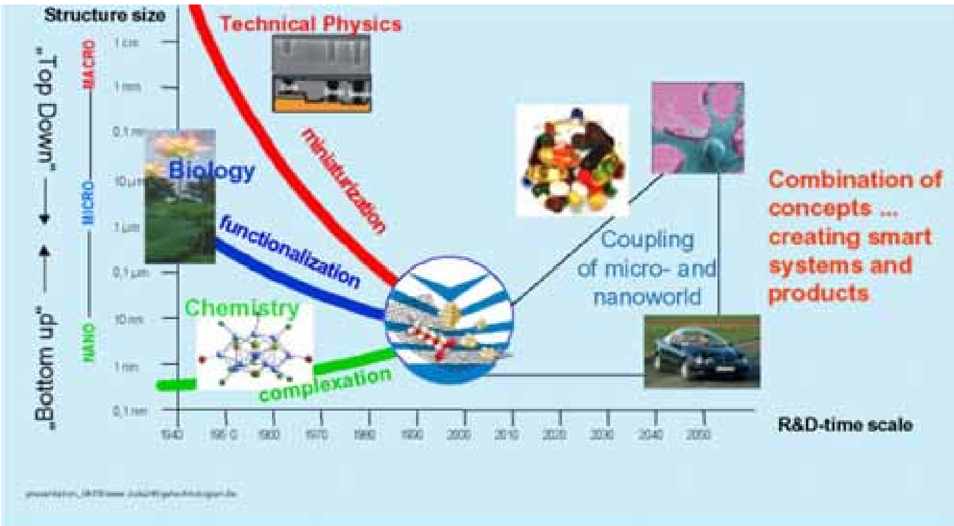

Figure 3. Multi-disciplinarity and combination of paradigms (Luther 2004a).

The nanotechnological conglomerate is often divided into the following subsections: nanostructured materials, nanoelectronics, nanophotonics, nanobiotechnology and nano-analytics (Luther 2004b). These reflect however, more the nanoprefix being added on to existing research areas than the development of novel nanospecific technological domains.

In the following six characteristics important for the dynamics of nanotechnology development are given (see Cientifica 2003; Selin 2004; The Royal Society 2004; Wood and Geldart 2003; Luther 2004b):

- *It is a platform technology* characterized by boundary problems, where it is contested what is nanotechnology and what is not. It is still discussed whether nano is a new technology or just a hype that re-labels existing practices.
- The *enabling nature* of the technology. It is a very fundamental (as fundamental as it gets) general-purpose technology. There are expectations of wide systemic effects on practically any technology.
- The *immaturity and science-based nature* of the technology. We are mainly talking about fundamental research. The industrial applications of nanoscience are in many cases only starting to take place, and the scope of many potential (theoretically possible) nanotechnologies is highly uncertain.
- The *ubiquitous nature* of the technology. Being so small, nano materials can be built into (existing or new) materials and devices, leading to a high degree to converging (smart) technologies with multiple functions. It can, however, also be used to build completely new materials.

- The *cross-disciplinarity* of the field. Nanotechnology is the convergence of several natural scientific disciplines.
- The inherent *spectacular nature* of the technology. Nanotechnology deals with and changes fundamental aspects of life (atoms and molecules). It is frequently stated that nanotechnology will "reshape the world atom by atom" or similar statements. Hype and fantasizing lead to great long-term expectations but also confusion and uncertainty and serious concerns about the scope and societal and environmental effects of the technology.

In the Danish empirical analysis in section 4 and 5, we return to these issues.

2.2 The nanotechnological development

Currently, nanotechnology is hardly a technology. Much nanoscience has not yet materialized into technologies. Major problems remain concerning how to scale up slow research laboratory work to efficient industrial mass production. But internationally, investments in nanotechnology are increasing tremendously, which reflects the high expectations for nanotechnology. An ongoing global race is on to be in the lead of a potential industrial revolution. US is currently in front, but Asia is also very much on the move with EU lagging somewhat behind (Lux Research 2004)..

National and local governments across the world planned to invest close to $5 billion in nanotechnology R&D in 2004 (35% in the US, 35% in Asia, 28% in Europe, and 2% in rest of the world). Corporations planned to spend about $4 billion globally on nanotechnology R&D in 2004 (46% by US firms, 36% by Asian firms, 17% by European firms, less than 1% by companies in the rest of world) (Lux Research 2004).

Quite a range of products are already commercial, but mainly on a small scale and mostly based on top-down techniques; e.g. in cosmetics, textiles, paints and electronics where many are used in the automotive industry and mobile phones. In mobile phones, for example, nanotechnologies are used in advanced batteries, electronic packaging and in displays. Numerous forecasts have been made on the future development of nanotechnologies. The uncertainty is considerable, but major breakthroughs are expected in a range of areas within the next 5 to 15 years, although some developments may have even longer time perspectives (Lux Research 2004, Cientifica 2003).

2.3 Explaining path creation in nanotechnology

This analysis applies an innovation economic perspective to nanotechnological development. The perspective pursued here seeks to place nano innovation dynamics within an innovation system perspective (Freeman 1987; Freeman 1995; Lundvall 1988, 1992 (ed.); Nelson 1993; OECD 2000, 2002). The (national) innovation system perspective (NIS) entails a theory on the co-evolution of institutions, organizations and technology. Hence, an innovation system is defined as "those elements and relations, which interact in the production, diffusion and use of new and economically useful knowledge" (Lundvall, 1992). The NIS perspective forms today the basis of much innovation and research policy (OECD 1999, 2000; European Commission 2002).

A main question is how nanoscience is going to be caught up by the (national) innovation systems when materializing into technologies. Who are the main actors; what are the drivers; and what will the stages of development be? The empirical analysis in section 4 seeks to investigate the evolving "nano innovation system" in Denmark, i.e. how research institutes and companies interact in the production of nano knowledge under influence of and in co-evolving with surrounding nano-specific institutions.

Nanotechnology is highly science-based. Public research and not least major multinational companies are currently the main drivers of nanotechnology development (Lux Research 2004; Cientifica 2003). Since it is a general purpose technology, similar to the steam engine, electrification and ICT, it is very generic and enables other technologies rather than creating products on its own. Nanotechnologies may serve as e.g. raw materials or ingredients or additives to existing products. Although nanotechnologies may physically only make up a small portion of various products, they may exert an influence on their properties in decisive ways. Nanotechnological development is likely to influence practically all technology spheres, but it is a question how much it will complement or replace existing technologies.

General-purpose technologies, if materialized, exert profound long-term effects on the economy, i.e. they create long waves in the economy. The gestation time may be very long though, often 30 to 50 years after early breakthroughs (Freeman and Loucã 2001). Wider effects on the aggregate economy only materialize during the mature stages of the technology. So far, the economic impacts of nanotechnology are very limited. We are still awaiting a possible technological and economic take-off in the wake of the current massive worldwide investments in nanotechnology.

Due to the infancy of nanotechnology, the focus here is on early path creation, i.e. the early structuring of the field. Nanotechnology is very much in the *pre-paradigmatic stage*. From the innovation cycle literature we know something about the processes in this formative phase. In this fluid phase, uncertainty about future innovation paths is great. It is uncertain whether the innovation will become a dominant design or not, and there is risk of exaggeration. This makes it difficult to persuade other researchers, firms and investors to support the innovation (Teece 1986; Lundvall 1985). Creating confidence in a standard based on a trajectory that is hardly understood, such as nanotechnology may easily appear, is naturally associated with great difficulty. Such radical changes manifest themselves slowly and have to await a codification process and gradual acceptance of principles through multiple interactive learning processes between supporters and opponents.

In the very early stages of a technology, standardization activities are focused on the creation of a common language. Next, the performance expectations and procedures for inspection, testing and certification are addressed (Reddy et al. 1989). The codification process may possibly be succeeded by changes in educational systems and other supporting infrastructure. During this stage, appropriability conditions are weak, and imitation is strong. Market leadership is required to advance standards, and it is often the big players with strong reputations who break the logjam among rival technologies and pull the complementary assets (technologies and capabilities) together (Chesbrough and Teece 1996).

If we turn to the *paradigmatic stage*, as industry standards increasingly become accepted, economies of scale and learning become more important. Imitators with lower developing costs who are less restricted by asset specificities, rather than the innovators, may come to possess the dominant design and profit from the innovation (Teece 1986).

Since much nanotechnology is still only nanoscience or is at the early experimental stage, we are talking about very early path creation.

Path creation

Path-dependent learning implies that a research organization's or a firm's knowledge base is theory-laden and maintains inner consistency. The basic argument, inspired by Kuhn (1970), is that technology development, parallel to scientific work, follows certain heuristics. Dosi (1982 p. 152) defines a technological paradigm as "a model and a pattern of solution of selected technological problems, based on selected principles derived from natural sciences and based on selected materials technologies" (p.152). *A technological trajectory is the pattern of conventional problem-solving activity within a given technological paradigm*; i.e. it is the normal problem-solving activity determined by a paradigm (Dosi 1982).

The technological path (or trajectory) emerges because the technological paradigm embodies strong prescriptions for the directions of technological change to pursue (positive heuristics) and those to neglect (negative heuristics) (Dosi 1982). The efforts and imaginations of researchers and practitioners are focused in precise directions, while they are "blind" with respect to other technological possibilities. A technological paradigm defines an idea of technological "progress" related to the economic and technological trade-offs of a given technology.

Many elements in the innovation system contribute to the "seeding" of trajectories: "Microlevel entities path-dependently learn (and get stuck).., but sector-specific knowledge bases and country- specific institutions restrict the 'seeding' of the evolutionary process ... and also channel the possible evolutionary trajectories. ... Given the initial conditions and the institutional context, these innovations spread and set in motion a specific trajectory of competence-building and organizational evolution" (Dosi and Malerba 1996 p.15).

The core question addressed in this study is the directions of the emerging nanotechnological trajectories and how environmental issues may form a part in these. The perspective suggested here is to analyse nano path creation dynamics by focusing on the shaping of researchers' and firms' *attention rules*, i.e. the routine problem focus of their research or technological development work (compare Penrose 1956; Boisot 1995) and their *search rules*, i.e. their routine learning modes (Nelson and Winther 1982). The formation of attention and search rules is placed within a wider analysis of the organization of (nano) knowledge production within the innovation system (Lundvall 1992, ed.; OECD 2000).

These aspects are discussed further in the analysis of path creation in the Danish nano community in section 4.

To conclude, there are limitations as to how much can be said about emerging technological paths in nanotechnology, given the current immaturity in technology development and great uncertainty as to the scope of the technology. We know in fact very little at present about how nanotechnology will materialize itself.

3 Nanotechnology - international findings on environmental risks and opportunities

3.1 Environmental risks related to nanotechnology

Until recently there has been very little research into nano-related risks. Thus, health, safety and environmental impact assessment of nanoparticles and nano-materials are encumbered with huge uncertainties due to lack of knowledge.

Increasing attention is being paid by authorities, however, to nano-related risk issues, and several surveys are underway around the globe[1]. In the US national nano initiative, by far the biggest nano research programme globally, it is stated that “increasing knowledge of the environmental, social and human health implications of nanotechnology is crucial” (NSET 2003 p.32). In USA, the Office of Research and Development at the Environmental Protection Agency has requested studies to be made on the environmental effects of nanotechnology. French (ECODYN) and Asian studies are underway, e.g. in Japan. In its proposal for a European strategy on nanotechnology, the EU Commission (2004b p. 20) also emphasizes the potential risk for human health and the need for research and precaution. A number of research projects on the safety of nanotechnology are being funded by the European Commission within the Fifth and Sixth Framework Programme. Among these, is the ongoing NANOSAFE project, which assesses the risks involved in the production, handling and use of nanoparticles in industrial processes and products, as well as in consumer products.

Concerns of nanotechnology are particularly related to:

- The particles’ large surface area, crystalline structure and reactivity, which could facilitate transport in the environment or the body that could be difficult to control or harmful because of their interactions with other elements. Some manufactured nanoparticles will be more toxic per unit of mass than larger particles of the same chemical.
- Ultrafine particles that have a different biological behaviour and mobility than the larger particles. There is no linear relationship between mass and effect. It is likely that nanoparticles will penetrate cells more readily than larger particles.
- The “invisible” size of the particles being developed. Such particles could accidentally enter into the food chain, initially causing damage to plants and animals while eventually becoming a hazard to humans. An expected wide-reaching spread of nano materials in products and the environment could make them difficult to contain and control (Nanoforum 2004; Jong 2004; EC Sanco 2004; Royal Society 2004).

The evaluation of risks related to nanoparticles is complicated by the fact that they already exist widely in the natural world, e.g. as a result of photochemical and volcanic activity or being created by plants and algae. Some of these are highly toxic. They have also been created for thousands of years by man as a by-product of cooking and combustion and more recently vehicle exhaust. The question is then whether manufactured nanoparticles or the use of nanoparticles in new ways present new risks?

1 For an overview of these, see chapter 7 in Nanoforum (2004).

The most significant conclusion of the recent/ongoing risk studies is a likely health risk related particularly to *free nanoparticles* that may penetrate into the brain, lungs and other tissues and possibly cause cancer and other deceases. Nanotubes have properties quite similar to asbestos fibres, which raises suspicion of a similar toxicity (Royal Society 2004; Nanoforum 2004; Luther 2004b; EC Sanco 2004).

Most of the risk studies, however, focus on health and safety aspects while the impacts of nanotechnologies on the environment have not yet been studied thoroughly. The Royal Society report concludes that "there is virtually no information about the effect of nanoparticles on species other than humans or about how they behave in the air, water or soil, or about their ability to accumulate in the food chains" (Royal Society 2004, the summary). They recommend that until more is known the release of nanoparticles and nanotubes to the environment should be avoided as far as possible, and that a precautionary principle should be applied.

A series of environmental assessment analyses are under way around the globe, but so far only few results are available. One of these is an on-going study from CBEN – Rice University examines the behaviour of TiO_2-nanoparticles and carbon nanotubes in the environment with emphasis on the interactions with other chemical species. To follow up on this, researchers will work on transport and aggregation of nanoparticles as well as their interaction with biological systems (CBEN 2004). It was observed that fullerenes could migrate through soil without being absorbed (Nano-forum 2004). On the other hand, not all nano materials were mobile in water. Mobility is very case specific (www.nanotechweb.org, 1April 2004).

A rare example of a study is on the ecotoxicological effects of the carbon molecules called "buckyballs" (fullerenes) that show that these cause brain damage in fish at concentrations of 500 ppb (Oberdörster 2004). It matters what kind of nanotechnology we are talking about and how it is used. According to Put (2004), the following classification can be used for the purpose of mapping out risks related to nanotechnology:

- Nanostructures from whatever nature (nanopatterns, nano-ordering, nanoparticles) that are *immobilized* at the surface or in the bulk of a matrix material. This kind of nanostructuring creates very little risk as the nanostructures or nanoparticles are fixed in a matrix.
- Nanoparticles that *are free* and can become airborne to form an aerosol. Depending on the shape of the particles, they can be breathable and upon inhalation cause adverse effects. These effects are related to the enormously enhanced surface to masse ratio and all properties related to surface will be multiplied with a huge factor.
- Supramolecular nanosystems, built up via *self assembly*, mimicking natural systems. Although these nanosystems might look like natural systems, there is one essential difference; they are not self-replicating, and it is unlikely that self-replicating systems can be built up on short notice. There seems currently to be less concern with the so-called "Grey Goo fear" of uncontrolled self-assembly, as pointed out by Drexler (1991).
- Nanosystems of *natural origin*. Natural nanosystems can be extremely dangerous or poisonous. Since these systems are self-replicating or belong to self-replicating organisms and moreover as some of them are continuously modifying themselves via exchange of genetic material (e.g. viruses), these nanosys-

tems have to be considered the most dangerous on this planet, although they are not perceived as such. Certain natural systems are genetically modified because this can enhance beneficial properties substantially (e.g. enzymatic catalysis). However, new insights in genetics have led to the conviction that not all consequences of even simple genetic modifications can be predicted; therefore, genetic modification should be limited to micro-organisms, where containment is possible.

The above categorization, however, says little about the environmental impact of different nano manufacturing techniques and thereby also of different nanotechnologies and nano materials. Of this very little is known so far. The Nanoforum 2004 report states: "*Differences in size, shape, surface area, chemical composition and biopersistence require that the possible environmental impact be assessed for each type of nano material. The long-term behaviour of such substances and their effects on elements are thus extremely hard to foresee*".

Table 1 summarizes the results of an environmental assessment performed in Germany by IÖW on the different nano manufacturing methods, one of the few studies made on this so far. As shown it is anticipated that risk of release of nanoparticles is low for most production and uses of nano materials. Highest risks occur in work environments when processing airborne nanoparticles. However, even if the release from materials may be low, a widespread use of nanotechnology might possibly lead to a dispersion of significant amounts of nanoparticles. We need to know more about the behaviour and potential hazards of artificial nanoparticles in the environment.

Table 1. *Nanotechnological products, their probable manufacturing process and their potential hazards.* (Haum et al. 2004)

Nanotechnology based products	Nanostructure	Manufacturing process	Potential hazards	Industrial sector
Application Area: New Surface Functionalities and Finishing				
tribiological layers: e.g. superhard surfaces	ultrathin layers; nanocrystallites; nanoparticles in an amorphous matrix	vapour phase deposition, PECVD	PVD/CVD production process: risk of disposal of nano-particles is small (process is run in a vacuum environment) use stage: low scale disposal of nano-particles possible	Engineering, automotive
thermal and chemical protection layers	ultrathin layers; organic-inorganic hybrid-polymers; nanocomposites	vapour phase deposition; sol-gel		aerospace, automotive, ICT, food
self-cleaning and antibacterial surfaces	ultrathin (polymer) layers, nanocrystallites in an amorphous matrix	vapour phase deposition, sol-gel, soft lithography		textile, ICT, food, building, medicine...
Scratch resistant and anti-adhesive surfaces	ultrathin layers; organic-inorganic hybrid-polymers	sol-gel; SAM	use stage: low scale disposal of nano-particles possible	building, automotive, textile, consumer goods
products with "nanoparticle effects" : e.g. colour effects in lacquers	nanoparticles, ultrathin layers	flame assisted deposition, flame hydrolysis, sol-gel	production: deposition possible; use stage: low scale disposal	building, automotive, consumer goods, textile

			possible	
Application Area: Catalysis, Chemistry, Advanced Materials				
catalysts	nanoporous oxides, polymers or zeolithes; ultrathin layers	precipitation, sol-gel, SAM, molecular imprinting	not known	chemistry, automotive, environmental, biotech
sieves and filtration	sintered nanoparticles, nanoporous polymers	self assembly, colloid chemistry		chemistry, environmental
Application Area: Energy Conversion and Utilization				
fuel cells	ceramics from sintered nanoparticles	div.	not known	energy, automotive
super-capacitors	Nanotubes, nanoporous carbon aerogels	div.	nanotubes possibly toxic when inhaled	energy
superconductors	ultrathin layers	e.g. vapour phase deposition	production: risk of disposal is small	energy, medicine
Application Area: Construction				
Nano-scale additives: e.g. carbon black in car tires	nanocrystals and nanoparticles	flame assisted deposition, flame spray pyrolysis	production process: disposal of nanoparticles possible, danger of inhaling for workers; use stage: low scale disposal of nanoparticles possible	building, automotive
Application Area: Information Processing and Transmission				
nanoelectronic components	ultrathin lateral nanostructured semiconductor	PVD, CVD, lithography	PVD/CVD production process: risk of disposal of nano-particles is small	ICT
displays	utrathin layers	PVD, spin-coating		ICT, automotive
Application Area: Nanosensors and Nanoactuators				
sensors: e.g. GMR-sensors	metallic ultrathin layers; ultrafine tips	CVD/PVD/MBE; etching, SAM	PVD/CVD production process: risk of disposal of nano-particles is small	automotive, engineering, ICT, analytics
probes: e.g. for scanning tunneling microscope	utrathin layers, ultrafine tips and molecules	PVD, etching, SAM		analytics
Application Area: Life Sciences				
active agent carrier: e.g. drug carriers	organic molecules, nanoporous oxides	self assembly, anodic treatment	flame hydrolysis production process: dis-	Pharma, medicine

Cosmetics: e.g. pigments	utrathin layers from nanoparticles, (amorphous) nano-particles	wet-chemical separation; colloid chemistry	posal of nanoparticles possible; use stage: particles might be absorbed dermally; very small TiO2-particles possibly toxic	cosmetics
sunscreen	nanocrystalline titanium dioxide (TiO2)	flame hydrolysis		cosmetics

Environmental impacts in the product cycle

Life Cycle assessment is an environmental management tool for assessing the environmental impacts of a service or function. All use of materials, resources and energy as well as all emissions from the processes in the life cycle are aggregated and interpreted in terms of their impacts on the environment and health, e.g. their contribution to global warming, acidification etc.

As described above specific concern is related to the release of free nanoparticles. An inventory of possible sources of potential particle release from the use and production of nanoparticles can be made by addressing the life cycle from nanoparticle generation to end products and finally disposal. It must be stressed that due to the variety of different production methods, the process conditions vary widely; thus, in principle the risk of potential particle release has to be considered separately for each different process.
The following main steps can cause unintended release of nanoparticles (Luther 2004c p.44-48):

Nanoparticle production. In processes working at high temperatures or with high-energy mechanical forces, particle release could occur in case of loss of containment of the reactor or the mills. Large quantities of nanopowder could be released into the atmosphere in a short time. Moreover, when sealing is broken, reactive mixtures can come into contact with air and in some cases cause violent exothermic reactions. Failure of the collecting apparatus is also an important source of potential release; this apparatus must be able to stop the nanoparticles and to evacuate effluents produced from the processes.

Collection of nanoparticles. Risks increase during the collection of nanoparticles, particularly in dry form. When opening the collecting apparatus or reactors, nanoparticles can be released and airborne dispersed due to their high volatility. In gaseous atmosphere, the behaviour of dry nanoparticles is primarily determined by the balance between attractive and lift forces. Gravity force has no noticeable effect on nanoparticles. Therefore, nanoparticles may be an air contaminant for a long time, potentially being an inhalation health risk. When handling small particles, conditions for dust explosions may arise, especially in case of metal powders. Once dust has formed in the proper mixture with air, it can be ignited by energy from various internal or external sources. During the collection of solid nanopowders, special care must be taken with regard to ventilation at the workplace. Air streams could disperse nanopowders to form aerosols.

Cleaning operations. Nanoparticle release can also occur during cleaning operations of reactors, after the disassembling, when nanoparticles have to be removed from stainless steel pieces, windows or filters. Cleaning is usually performed using solvents or water, tissues, brushes or sponges, which are then discarded in garbage cans.

Handling and conditioning operations. Risks related to this kind of operation can be release of nanoparticles while producing ceramic pieces, particularly when compressed nanopowders or coatings are formed.

Waste disposal. This includes the total production equipment that has been in contact with nanopowders at the different steps in production. Disposal of waste might be a potential source of nanoparticle release into the environment if no special care is taken concerning traceability and the final disposal or combustion of wastes.

Final product utilization. When final nanoparticle-based products are obtained, risks depend on the way in which nanoparticles are integrated. For nanostructured materials, nanoparticles are linked to a matrix by thermal treatment at high temperatures. However, under wearing conditions, particle release is likely to occur, but dissociation of matter at the nanometric scale is unlikely.

Some of the fundamental features of nanotechnology that are essential for the new opportunities nanotechnology offers may also be a drawback when it comes to risks. We have a natural fear of what we cannot see, cannot control and cannot understand. And this is how nanotechnology may easily appear.

Policy initiatives on nano environmental risks

Existing regulations indexing chemicals and measuring new products' toxicology need to be adapted to the special properties of nano-materials. According to Nanoforum (2004), nanotechnology leads to a need for new norms, standards and testing procedures for assessing risks to the environment and health (e.g. for nanometer length scales, calibration of instruments, health effects of nanoparticles, toxic effects of nanometer size of particles rather than on their chemical composition).

Recently, considerable attention is being devoted to the issues of regulation and legislation of risks related to nanotechnology, particularly in USA and Europe. However, the practical set-up of new legislation or adaptation of existing legislation is still in its infancy. It can be said that most countries and international institutions are still in the phase of raising awareness and investigating what the regulated topics should be (Nanoforum 2004).

The European Parliament's Industry, External Trade, Research and Energy Committee has called for a study on the need for new regulations on nanotechnology, while the same subject is to be discussed by the UK's Parliamentary and Scientific Committee.

In the nanostrategy of the European Commission from 2004, the following actions are recommended in relation to public health, safety, environment and consumer protection (p.20):

- to identify and address safety concerns (real or perceived) at the earliest possible stage
- to reinforce support for the integration of health, environment, risk and other aspects related to R&D activities together with specific studies
- to support the generation of data on toxicology and eco-toxicology (including dose response data) and evaluate potential human and environmental exposure

- the adjustment, if necessary, of risk assessment procedures to take into account the particular issues associated with nanotechnology applications
- the integration of assessment of risk to human health, the environment, consumers and workers at all stages of the life cycle of the technology (including conception, R&D, manufacturing, distribution, use and disposal) (European Commission 2004b).

The recent Nano Technological Foresight's Danish Nano Action Plan suggests that there should be focus on studies of possible health hazards and environmental and ethical aspects associated with nanotechnological industrial processes and materials and other applications of nanotechnology (Videnskabsministeriet 2004). The Nano Action Plan "recommends that as an integrated part of each individual project, funds should be allocated to research and competence-raising relating to the environmental, health and ethical issues raised by nanotechnology, and that the responsibility for this should rest upon the research environments that receive project funding. Projects should only be granted funding if they address the environmental, health and ethical aspects in a responsible manner" (Ministeriet for Videnskab, Teknologi og Udvikling 2004).

3.2 Environmental opportunities related to nanotechnology

There are often very high expectations as to the environmental benefits from nanotechnology in nano reports and policy statements (see e.g. The Royal Society 2003; Masciangioli 2002; Nanoforum 2004; Luther 2004b; NSET 2003). In fact, there are few nano reports, if any, that do not mention environmental opportunities as a core benefit of the technology. This is also the case with the recent Danish Nano Foresight report (Ministeriet for Videnskab, Teknologi og Udvikling, 2004). In other words, there seems to be an unusually strong linkage between nanotechnology and environmental benefits.

Some of these reports point to some fundamental features of nanotechnology with eco-potentials. Nanoforum (2004), for example, argues that self-assembly, i.e. the attempt to mimic nature's intrinsic way of building on the nanometre scale, molecule by molecule through self-organization, has eco-potentials:

"This 'assembling' method is extremely efficient and could be helpful for the conservation of nature and natural resources. It is expected that the concept of 'self-assembly' could be an approach for a sustainable development in the future. However, such futuristic concepts are far from being realized at present or in a medium-term view (Nanoforum 2004 p.39).

Another report points to the energy efficiency of nanoparticles:

"The most relevant effect of nanoparticles for energy applications is the large amount of the atoms exposed on the surface compared to the bulk material. The large surface area leads to a high reactivity with low material use, which is useful for better catalysts (leading to higher reaction rates, lower processing temperatures, reduced emission or need for less material), for improving combustion processes (higher efficiency, lower processing temperatures, or higher absorption rates for light" (Nanoform 2003 p.89).

The big US National Nano Initiative holds a strong overall green vision: "Nano-scale science and engineering can significantly improve our understanding of molecular processes that take place in the environment and help reduce pollution by leading to the development of new "green" technologies that minimize the use, production and transportation of waste products, particularly toxic substances. Environmental remediation will be improved by the removal of contaminants from air and water supplies to levels currently unattainable, and by the continuous and real-time measurement of pollutants" (NSET 2003 p.32).

Another grand and quite green vision is expressed by a nano roadmap of the chemical industry stating that in the longer term it is hoped that "nanomanufacturing will encompass genuine 'green' concepts of zero waste and little or no solvent use incorporating life cycle concepts of responsible products coupling biology with inorganic materials" (www.ChemicalVision2020.org).

Jacobstein (2001) and Reynolds (2001) pinpoint perhaps most sharply four main features of nanotechnology that are likely to lead to environmental benefits:

- The atom-by-atom construction of nanotechnology will allow the creation of materials and products without dangerous and messy by-products.
- Most products of nanotechnology will be made of simple and abundant elements; carbon e.g. is the basis of most nanomanufacturing.
- Less materials will be needed because nano materials are stronger and thinner.

Cheap nano materials with a very high strength to weight ration could mean a marked drop in energy consumption, e.g. in transport.

Malanowski (2001), in referring the results of a workshop, similarly concludes that the ecological benefits of nanotechnology could be very large in the following ways:

- Preservation of resources is expected through the production of miniaturized products that with a smaller material expenditure fulfil the same functions as conventional products.
- Energy savings could be achieved in transport through weight and volume reduction of products and by the reduced consumption costs of energy-saving electronic production processes.
- The use of wear-resistant machine parts, corrosion-proof materials, nanolubricants and/or nanotechnological procedures for the smoothing of surfaces contributes to the extension of machines' service life.
- New materials will show greater stability with comparatively small specific weights than conventional materials and will likewise contribute to the preservation of resources and e.g. reduced fuel consumption in cars.

Claims such as the above are often of a quite general and theoretical character, and many findings are merely based on workshops rather than thorough analyses. There is a lack of more careful and systematic in-depth studies of the extent and nature of eco-potentials. This is naturally related to the early stage of development of the nanotechnologies and the associated high degree of uncertainty. It seems to be too early to be very specific about where the opportunities are; and/or the eco-opportunities have not been looked into properly so far.

Numerous more specific potential environmental benefits of nanotechnology are pointed to in the literature, though more as examples and visions than as an attempt to be comprehensive or to identify the most significant environmental potentials. Some of those frequently mentioned are (The Royal Society 2003; Masciangioli 2002; Nanoforum

2003, 2004; Luther 2004b; Antón et al. 2001; Malanowski 2001; European Commission 2004; NSET 2003):

Reduction of energy consumption

- Through a) better insulation systems using nano-porous materials, b) through more efficient lighting (nanotechnological approaches like LEDs (Light Emitting Diodes) or QCAs (Quantum Caged Atoms) are much more energy efficient), c) through more efficient combustion systems, d) the energy consumption in the mobility sector can be reduced by the use of lighter and stronger nanostructured materials (see the automotive industry below), e) synthetic or manufacturing processes can occur at ambient temperature and pressure.

Develop more efficient or renewable energy production.

- The degree of efficiency of combustion engines is not higher than 15-20 percent at the moment. Nanotechnology can improve combustion by designing specific catalysts with maximized surface area.
- Nanotechnology is important for the development of hydrogen energy systems in several ways. Attempts are being made to develop fuel cells powered by hydrogen fuel. The catalyst in fuel cells is nanostructured materials consisting of carbon-supported noble metal particles with diameters of 1-5 nm. Suitable materials for hydrogen storage contain a large number of small nanosized pores. Therefore, nanostructured materials like nanotubes, zeolites or alanates are under investigation.
- Nanotechnology can help to increase the efficiency of light conversion in solar cells through specifically designed nanostructures (the implementation of Nanodots). The widespread use of solar cells suffers from the high costs of purchase. An alternative nanotechnological approach under development is low-cost solar cells using titanium dioxide nanoparticles as light absorbing components (Grätzel cells). This may allow for more decentralized energy supply systems.

Reduction of resource consumption in the production or user phase:

- Nanoparticles in paint can induce new properties to the paint, e.g. cooling effects, self-cleaning and self-repairing surfaces.
- Nanotubes (or fibres built from them) can be used as reinforcement for composite materials. Because of the nature of the bonding, it is predicted that nanotube-based material could be 50 to 100 times stronger than steel at one-sixth of the weight, if current technical barriers can be overcome.
- Strengthening of polymers in order to produce new materials with less consumption of raw materials that can substitute existing materials
- Reduced use of rare resources such as precious metals or toxic substances in catalysts.
- Textiles with nanotechnology finish can be washed less regularly and at lower temperature.

Improved cleaning of air, water and soil through the development of new environmental catalysts and improved catalytic processes as well as improved capability to tailor nanostructured membranes, which offers new opportunities to selectively extract contaminants from air, water and soil.

Improving recycling

- The use of batteries with higher energy content, or the use of rechargeable batteries or supercapacitors with higher rate of recharging using nano materials, could limit the battery disposal problem.
- Integration of nanochips in materials and products containing information about material properties and composition can be used for recycling purposes. (There are, however, also arguments that multifunctional nanoproducts may be difficult to recycle).

Better monitoring

- Nanotechnologies are expected to enable the production of smaller, cheaper sensors with increasing selectivity, which can allow continuous measurement and be used in a wide range of applications, e.g. monitoring the quality of drinking water, detecting and tracking pollutants in the environment.

Reducing the environmental impact of the automotive industry

- One area where nanotechnology is expected to contribute with major eco-innovations is in the automotive industry (Nanoforum 2004). Rising traffic density means that transport remains a major environmental problem, and the car industry is increasingly looking for new solutions, also among nanotechnologies. The car industry hence belongs to the earliest users of nanotechnology. The automotive industry is in other words an area where there are some more substantial insights and experiences with developing eco-innovations based on nanotechnology. These are therefore dealt with more in detail in the following. Some products mentioned below are already on the market, others are at the experimental level.
- Energy consumption and waste is reduced by replacing metals with lighter materials. Nanoparticles are used to improve the strength of lighter metals or of steel, so that less metal is necessary. Or using polymers reinforced with nanoparticles make them stronger per unit weight.
- The rolling resistance of tyres is lowered, thus saving energy, and the durability is improved by use of nano-scaled carbon black, thus saving waste.
- Combustion can be improved by homogenous and large area spraying of petrol. An injection system with very fine holes (Nanojets) is under development.
- Engine lubrication is optimized by new nanoparticle-based lubricants and through micro- and nanostructures on the inner surface of the cylinders.
- Engine efficiency is optimized by use of higher temperatures and pressures. Nanotechnology can help to develop materials that are resistant to these conditions.
- Use of environmentally more friendly energy systems in cars. Thermoelectrical elements based on nanocrystalline layers of semiconductors with low band gaps may use part of lost heat in the future. Cheap (e.g. dye solar cells) or more effi-

cient types of solar cells (e.g. through the implementation of Nanodots) can be used in the roof for operation of specific modules (e.g. for air conditioning systems), possibly be enlarged to the whole chassis. Experiments with cars driven by fuel cells are extensive.

- Reduction of air pollution caused by exhaust gas. Nanotechnology can contribute to the further reduction of pollutants by nanoporous filters that can clean the exhaust mechanically, by catalytic converters based on nano-scale noble metal particles, or by catalytic coatings on cylinder walls and catalytic nanoparticles as an additive for fuels.
- Developing new understandings of molecular processes that take place in the environment (e.g. how contaminants move through the environment) is also highlighted as an important environmental benefit of nanoscience (NSET 2003).

Overall, the environmental benefits of nanotechnologies are not as yet described in very great detail or systematically, and life cycle assessments are often lacking, i.e. investigations of the environmental impacts of nanotechnologies over the complete supply chain including disposal.

A few case studies have been made that examine the eco-potentials of nanotechnology in more depth, notably a recent German life-cycle assessment study (Steinfelt et al. 2004). Four case studies are analysed: Nano varnish, nano innovation in styrene synthesis, nano in the display sector, and nano in the lighting sector. The study illustrates that at this point it is very difficult to make high-standard quantitative assessments of the environmental impact of nanotechnologies due to lack of knowledge, incompleteness of available data on a given product or process, and the high uncertainty as to future technology development.

The most important recent environment assessment report, the Royal Society report (2004) mentioned earlier, does not look into eco-potentials, except for stating that “it is important to substantiate such [environmental] claims by checking that there are indeed net benefits over the life cycle of the material or product” (Royal Society 2004 p.32). It is recommended that a series of environmental assessment studies be undertaken by independent bodies on existing and expected developments in nanotechnologies.

Policies towards nanotechnology, e.g. EU’s nano strategy and the suggested Danish nano action plan, focus mainly on risk issues when dealing with environmental impacts and do not aim to address barriers to eco-innovation. So although the eco-potentials of nanotechnology are highly praised, they seem rarely to be promoted by policies. An important exception is the US National Nano Initiative, where “Nano Scale Processes for Environmental Improvement” make up one out of nine Grand Challenge Areas for prioritized research; compare also the already mentioned strong green vision of the research programme (NSET 2003).

Interestingly, a first international initiative “International Consortium for Environment and Nanotechnology Research (I-CENTR)” has recently been created. It looks at both negative and potentially positive environmental impacts of nanotechnology. The consortium studies the environmental applications of nanochemistry, nano-scale materials and processes in the environment, nano material interactions with organisms and environment, and generally sustainable ways for applying nanotechnologies. This consortium gathers approximately 30 researchers from various French and US universities and is adding groups in Germany, Switzerland and England. Currently, the actual extent of nano research and development targeted at eco-innovation is not known. To conclude, also when it comes to eco-potentials there are many visions and claims related to nanotechnology, but so far there is only limited knowledge on the more specific potentials of nanotechnologies.

In section 5, where the focus is on the eco-potentials identified by Danish nano researchers, the eco-potentials are discussed further.

4 Danish findings on path creation in nanotechnology

This section presents the main empirical findings on the role of environmental issues in the search processes of Danish nano researchers and industry. The empirical analysis undertaken is a first scoping study into the actors and dynamics of nanotechnology development in Denmark, based 27 interviews in the Danish nano community as well as an interactive mail based survey and mapping exercise. No prior innovation analysis of this character has been made, so there is little data to build on or relate to apart from somegeneral findings and expert papers from a recent Danish general nanoforesight (Ministeriet for Videnskab, Teknologi og Udvikling 2004). Given the broadness of the technological field, there are limits as to the depth of analysis possible within this relatively limited project.

4.1 The emergence of the Danish nano community

In recent years, much has been happening within the nano area in Denmark. Several new nano research centres and networks are springing up: the biggest ones being Nano•DTU with the major subcentres -MIC, COM, ICAT and CAMP at the Technical University of Denmark, iNANO at the University of Aarhus with links to Ålborg University and the Nano-Science Centre at the University of Copenhagen. Some of these have been around for a while, 10-15 years, while others are new. Also, several transdisciplinary “nano educations” and ph.d. schools have been established, and with great success despite the general decline in students’ interest in the natural sciences. At the structural level, then, we clearly see the emergence of a nano research community.

These new centres reflect that some Danish funding has been earmarked for nano research, last year 60 mio. DKK, making the “nano” term increasingly attractive to researchers but forcing the nano researchers to join groups in order to apply for the money. There is little tradition in Denmark for large focused research efforts. Recently, the Danish Basic Research Fund and the new High Technology Fund are changing this somewhat, reflecting a stronger political interest in research and especially high technology in Denmark, including nano research. There are therefore expectations of more funding being directed to the nano field. As an input to the priorities of the High Technology Fund, the recent Danish nanotechnological foresight has suggested focusing the nano effort on two strong nano research centres with a budget of at least 100 mio. DKK/year. The outcome of these research strategic processes is as yet unknown however.

But how much hype and how much scientific novelty are involved in this nano trend? The Danish nano researchers are generally sceptical about the hype related to nanotechnology and its implications. To a large extent, many feel there is nothing new in nano. They do the research they have always done, but it is now redefined as nano.

On the other hand, the same researchers also expect that nanoscience will lead to greater changes in technology development, and some even anticipate an industrial revolution, albeit of a more evolutionary character. There is, in other words, a widespread sense of novelty and expectations of new industrial opportunities. Quite a few, however, express scepticism about the scope of industrial effects and warn that the hype may lead to too high expectations for nanotechnology and a back lash, especially in the short term.

At the more cognitive level, even though this may not be recognized by the individual researcher, a general conclusion of this analysis is that *attention rules* are changing as still more researchers, and more hesitantly people in industry, look towards “the bottom” for new problem definitions. *Search rules* are also changing in important ways, partly because researchers applying the new nano tools in their research area are gaining new understandings about the significance of size (of clusters) in relation to the properties of materials. Theory building and modelling are replacing trial and error experimentation in a range of areas, e.g. catalysis. This is partly because of the transdisciplinarity that is recognized as having a central role in much nanoscience. It seems that researchers from various disciplines find new grounds to meet at “the bottom” and synthesize their disciplines in new ways.

Danish researchers expect that the major innovations springing from nanotechnology will relate to the boarder areas between different disciplines, especially between biology – learning from natural systems – and physics/chemistry. New, more transdisciplinary paths are therefore to be expected. The effect of this, new search rules in various nano-related technological areas, however, are only in the making. The uncertainty about the direction of nanotechnological paths is at this time still huge.

All these signs of new patterns of problem-solving activities emerging indicate4 that nano is not only a language (a redefinition of existing practices), it is a technological trajectory that is however strongly shaped by the expectations associated with the nano hype.

These conclusions probably apply to nanotechnology in general and not only to Danish conditions. In fact, Danish researchers state that there is no such thing as a specific Danish approach to nanotechnology; it is basic science and very international, and regional specialization is limited. There are, of course, key Danish competencies and perspectives, which we shall return to.

The organization of the nanotechnological knowledge production in Denmark

Much is also happening to the organization of nano knowledge production as the field starts to shape up, and this calls for a deeper investigation. Here, only a few preliminary observations are presented.

The Danish innovation system is generally fairly low tech. There is a specialization on relatively low-tech and medium-tech products, an overweight of small companies, and few really big companies. Still, Denmark belongs among the more innovative economies and is doing quite well, not least through user-driven innovations and further development of products, albeit less engaged in radical innovation (Lundvall 1999; Innovation Scoreboard 2004). This raises questions as to the potential and conditions for building competencies on nanotechnology in Denmark given that nanotechnology is among the most science-based and high-tech technologies.

The Danish Nano Foresight Report especially points to characterization as the core competence within nanoscience and nanotechnology (Ministry for Science, Technology and Innovation 2004), which involves understanding and describing the phenomenon of nature and physics. Traditionally, less focus has been directed toward synthesis, that is, the use of these understandings for the creation of new materials and other technologies. The core nano competencies identified are within traditional natural sciences such as theoretical physics, quantum physics, optoelectronics, scanning probe microscopi, X-ray diffraction and biomolecules. Measured in publications, Danish nano research is at a medium level when seen in an international context, but it is at the top level on some areas such as catalysis. It has not been as good at translating this knowledge into industrial applications; however, this is seen as an advantage, since nanotechnology development is taking place closer to the world of fundamental physics research than to that of traditional industry (Ministry for Science, Technology and Innovation 2004).

Still, some nano researchers criticize Danish nano research in general for not being sufficiently oriented towards industrial application. A researcher at the Technical University states:

"In Denmark nano research is about understanding, modulization and characterization more than manufacturing. What we are in want of in Denmark is a centre for the design of nano materials. There are companies around the world becoming rich from selling nanotubes, fullerenes and tailor made materials. I see no reason why we shouldn't make this in Denmark".

There are some facilities and companies involved in nano manufacturing in Denmark, e.g. Danchip is Denmark's leading facility for micro- and nanotechnology, using conventional silicon integrated circuit technology for new areas within micro- and nanotechnology. Danchip is a part of Nano•DTU; however, it has not been possible to map the Danish nano equipment and manufacturing facilities in this study. Innovations based on micro/nano fabrication technology have played an increasing role over the last few years:

"Danish micro- and nanofabrication points both to applications within telecom and improving the bandwidth of the Internet, but also to new exciting possibilities with lab-on-a-chip applications, where complex diagnoses could be performed directly at the practitioner's office" (Professor Jens K. Nørskov, Head of Nano•DTU).

Danish nano research takes place primarily within the main public universities and research institutes in Denmark such as the nanocentres and networks already mentioned: mainly within the Technical University of Denmark (DTU), University of Aarhus (AU), University of Copenhagen (KU) and Risoe National Laboratory, and somewhat less at the Royal Veterinary and Agricultural University of Denmark (KVL), Ålborg University (AAU) and Southern Danish University (SDU). The technical institutes ("Approved Technological Institutes") are also involved to some extent in nano research with a strong application orientation.

With one exception, research within business is playing a minor role so far, although the relatively few big, research-oriented manufacturing companies in Denmark are involved to various degrees in nanoscience and -technology development and cooperate with the universities. Most important are companies within catalysis, medico and pharmacy, and somewhat less so those within advanced machinery and electronics and food ingredients.

In all, we are talking about less than ten big companies that are involved in nano research and are in a formal collaboration with universities, often in the form of co-financing PhDs. Some of these companies are, however, quite important to Danish nano research. Several nano researchers state that they miss the local presence of more big companies with strong scientific competencies to widen the opportunities for collaborative research with industry.

The one big company that stands out by playing a central role in Danish nano research and technology development is Haldor Topsøe, a leading world producer of environmental catalysts and steam reforming. Haldor Topsøe has 30 years of experience with large-scale nano-based production within catalysis. Catalysis is a traditional nanoscale technology, well developed through experimentation long before any talk of "nanoscience" started. Much of Haldor Topsøes research and technology development has accordingly been based on experimentation. The new understandings originating from the rise of nanoscience over the last 10-15 years are only beginning to make an impact on Haldor Topsøe technology development, and they are still waiting for them to result in major breakthroughs.

Haldor Topsøe has a very close relationship with the Danish research institutes, especially at the Technical University (Nano•DTU) and University of Aarhus (iNANO), and somewhat less at Risoe. The relationships are formal and so close that they could be called symbiotic. Haldor Topsøe pursues a conscious strategy of promoting Danish nano research and education, which they see as a necessary investment for them[2]. They not only collaborate with research institutes but also seek to strengthen them; e.g. in 1987, they took the initiative together with DTU to start research on Surface Science at DTU. This later materialized into CAMP and later also into the ICAT centre in 1999 with focus on catalysis. These and also the new Danish Research Foundation centre, CINF (Centre for Individual Nanoparticle Functionality), are very close collaborators with Haldor Topsøe A/S. Haldor Topsøe also invests in equipment at the universities, e.g. a new electron microscope costing 25 mio. DKK. It is central to Haldor Topsøe's competitive strategy to have a better understanding than their competitors of catalytic processes.

Haldor Topsøe is characterized by the nano researchers as being unique in its long sightedness and very strong research orientation that originated with the founder's strong passion for research. Ib Chorkendorff, Head of the ICAT and CINF centre, states:

"A company like Topsøe is different because of the philosophy there, which is very research based. Our competitors in Germany and England for example also cooperate with companies but these don't have the same interests in research. You can see a difference in the labs. The other catalyst plants haven't used so much money on equipment; they can't make the interesting investigations that Topsøe can make. This is what makes them so interesting as learning partners. We can talk to them directly. There are people there doing the same kind of research as we do. It is also interesting for our candidates who can see a career opportunity. This is what makes Topsøe a unique company. The close ties with industry are essential for our research."

He emphasizes the need to continue and strengthen the shift from the trial and error approach to more fundamental research within catalysis in the rising global competition:

2 Interview with Michael Brorson, Haldor Topsøe

“We don’t have a chance to compete with the Chinese who mix lots of potential catalysts over and over again looking for successful candidates. We need to find out what exactly the problem is, look at the physics behind it and then find out something new.”

General contact and cooperation with business varies considerably; some nano researchers have hardly any contact, others quite a lot. Industry links are somewhat stronger at the application-oriented Technical University and Risoe National Laboratory than at the traditional universities. A new analysis undertaken for the Danish Ministry of Science, Technology and Innovation confirms that these two institutes are in the lead in Denmark when it comes to business contacts, spin offs and commercialization of the research undertaken generally.[3] The large Nano•DTU centre seeks consciously to promote technology transfer to companies and has collaborations with around 50 Danish and international companies.[4]

Relations to business seem to be changing. “I see things are changing these years. Fifteen years ago the opinion was that here [at the university] we were to perform research at the highest level and educate people to the highest level, and that wouldn’t be possible if companies were involved. Today university researchers are much more open to interaction with business” (Researcher at iNANO).

Another researcher at iNANO states: “Earlier we had very little contact with industry, but now [since joining a think tank on nano application opportunities in the food industry last year] relations are very good. It has been quite an eye opener to learn about their needs.”

The Danish nano foresight report mapped 54 Danish companies working with or showing a strong interest in nanotechnology (Ministry for Science, Technology and Innovation 2004). Most of these are small spin-offs from the universities and/or small companies within nano instrumentation and measuring. In addition, we have the early users of nanotechnology, i.e. the large innovative companies in Denmark that cooperate with nano researchers on many of their projects. Actual industrial application of nano research is, however, still limited. Generally, the industrial uptake of nanotechnology is very limited in Denmark with the exception of the field of catalysis, in which, as elsewhere in the world, we are still far from widespread industrial application and up-scaling to mass production.

Company attitudes towards cooperation also seem to be changing. When discussing perspectives for a wider industrial nano development in Denmark, Professor Besenbacher, Head of iNANO states:

“I am very positive about cooperation with industry. It merely requires openness and a visionary attitude among the leading Danish companies. I clearly sense a considerable interest for nano, an interest which has increased over the past years. I think that the companies gradually realize that universities are leaders in this field, and they thus have a tremendous interest in interacting with us.”

A greater role is expected from established companies than new ones however. Professor Besenbacher states:

“The future role played by small start-up companies is yet unclear. The challenge is to go from fundamental blue sky research to industrial production, and with a time horizon of

3 Evaluering af Forskerpatentloven, Videnskabsministeriet 2004b.

4 According to Britt H. Larsen, Vice Director of Nano•DTU.

three years, there is no proof of concept, making it difficult to obtain financing in Denmark. It is much easier to attain risk capital in the US.”

A range of small, dedicated nano companies have emerged, however, especially within sensors, nanometrology and nanoparticle production, as illustrated in Table 24 in section 5.5,. These companies are typically spin-offs from the universities/research institutes. Their role in the uptake of nanotechnology in industrial production remains to be seen.

The Danish learning relations

The rise of the nanotechnological field is changing the learning relations in Denmark in important ways.

Ib Chorkendorff, Head of ICAT at the Technical University states:

“It is not a single or particular event or invention that has happened, which makes nano into something special, because we operate within the same circles as we have done the whole time, focusing at the atomic design. If I should say something about the nano hype, it is more that it leads to greater fragmentation; because every university wants its own nano centre. The new nano constellations mean that things have become more rigid.”

Cooperation between the new nano centres has to some degree diminished, particularly between Århus/Jutland (iNANO) and the research environments on Zealand (especially the Technical University). At the new Nano Centre in Copenhagen, they are now also looking towards Sweden (the Øresund region) for new cooperation opportunities.

The new regional nano centres disturb to some degree existing knowledge relations, since thematic specialization does not follow the regional clustering closely. In other words, nano research on the same themes is performed at several locations in Denmark.

All in all, the new nano centres have a marked impact on the organization of knowledge production, both negative and positive. On the positive side, the new nano centres are valued by their researchers, particularly because they facilitate interdisciplinary work. Actually bringing together researchers from various fields on a daily basis creates new opportunities for in-depth, long-lasting collaboration. The interdisciplinary way of working is surrounded by excitement. For example, a project on biocompatible materials at the iNANO centre in Århus brought together a molecular biologist, a physicist, and a medical doctor. In the beginning, they did not understand each other due to their different scientific backgrounds, but now they are getting somewhere: “It is quite new for us to operate with the interaction between solid surfaces and cells and proteins, but it has opened up completely new possibilities and has been quite exciting” (researcher, iNANO centre).

Nano•DTU, the largest cross-disciplinary centre for nanotechnology in Denmark, was established in 2004 to create synergy between the different research groups working in nanotechnology at the Technical University and use competencies and nanofacilities across departmental walls. More than 170 researchers are members of Nano•DTU; they come from nine different departments and around 14 different research groups, illustrating the wide research span of nanotechnology.

The nano centres have had a major positive impact on the ability to attract funding, researchers and interest from companies. The iNANO centre, although only two years old, sees a clear advantage in being well branded both nationally and internationally and especially in being more visible to companies.

Generally, learning relations between various departments at the same university or research institutions that are working with nano seem to be quite strong and are strengthened by the new, shared nano profile and the need to join forces to seek funds. Learning relations with international learning partners are also important, especially EU partners, in order to apply for EU funding. It is less relevant when it comes to cooperation with industry.

Nano-related research takes place at all Danish universities, at least if we do not define nanotechnology too rigidly. Research outside the new centres has problems attracting funds and attention (e.g. researchers at the agricultural university.

Generally, the nano researchers appreciate the nano innovation system in Denmark as it is now. A researcher at iNANO states:

“Research today is related to money. We must be able to attract the best researchers and the best equipment. Despite the small amount of funds I believe we can make a difference because we are a small nation. We practically all know each other. The same goes for the industry. The research leaders are scientists whom we know from our common university studies. I can pick up the phone and call, for example, the top people at Lundbeck directly. Our research groups have a non-hierarchical structure, as opposed to the Japanese structure in which two PhDs from different groups are not allowed to talk to each other without the permission of their respective boss. Our openness will be a decisive factor when the interdisciplinary projects are fully up-and-running.”

A researcher at the Technical University says: “At the moment it is excellent to do nano research in Denmark within my field [catalysis]. It is necessary to have a momentum, though, and you need fairly big groups to do this.”

4.2 Attention rules and entrepreneurial expectations

The nano research undertaken in Denmark is only partially driven by demand. To quite a wide extent, perceptions of possible application areas related to the research are quite weak. There is, in other words, an absence of entrepreneurial expectations in these cases and very little (technological) direction to the research undertaken.

The drivers for the choice of research focus for the interviewed nano researchers can be grouped into the following five categories:

- They do fundamental research. They are driven by an interest in understanding the dynamics at the nano-scale level in various ways.
- They are interested in doing something which has a big technological impact, i.e. affect many people (scope) or lead to major change (i.e. the hydrogen society).
- They are interested in solving serious problems, notably health care and energy supply, less so environmental issues.
- They are interested in themes which are important to Danish companies, partly because they are interested in strong local learning partners and partly because

they want to strengthen Danish industry and secure that public Danish investments in research create value in Denmark.

- They do research where they expect most funding to be found.
- They see regulation as an important driver of research and development, particularly in the energy and environmental areas (for catalyst and energy researchers only).

The limited application approach by some researchers can be illustrated by this statement by an iNANO researcher:

"Your end goal is not to make, e.g., a window which is self-cleaning, and then you start from scratch. Through research you suddenly obtain results which you may use to make a window. What we work with is definitely relevant for keeping surfaces clean, whether it is for an industrial machine or a window is up to the industry."

Another researcher describes the mix of inputs involved in forming the research agenda:

"Our ideas rise from interplay with colleagues, and the interaction with Danish and international companies is increasing. I would like to have money for fundamental blue sky research, but it is also satisfying when what you do has applications" (researcher from iNANO).

The nano path creation seems to become more pulled and less pushed in relation to the rise of nanotechnology:

Professor Besenbacher, Head of iNANO, states: "There is nanoscience and there is nanotechnology. There is no doubt that what we mainly do is nanoscience. We are inspired by an interest in understanding things at the molecular level. But I feel we are beginning to focus more on possible applications which could become nanotechnology."

Research at the nano centres at the University of Aarhus and University of Copenhagen seems to be more of a fundamental kind. At the Technical University, the nano research spans from fundamental research to applications. At Ålborg and Risoe, there is greater emphasis on the engineering aspect of nanotechnology, i.e. making devices.

Several of these researchers express interest in doing research that is of interest to Danish industry. For these researchers, then, the demand side is quite important in shaping the research agenda, also for more fundamental research, the demand side being industry rather than consumers.

There is, however, one application area that is a central focusing device. The dominant focus by far of Danish nano researchers is medico appliances; perhaps as much as 80 percent (a rough estimate) of the research is in some way oriented towards medico. This goes for all nanotechnology areas where it could be feasible, i.e. nano-modified materials or composites, functional surfaces, sensors etc. These research areas, then, are very little oriented towards other applications, despite the fact that they often have very wide application potentials. Issues such as biocompatibility, bacteria detection, antibacterial surfaces and drug delivery are at the center of most Danish nano research.

A researcher at iNANO explains:

"The research funding is so that we hardly have any basic funds for research, so we must find suitable projects. You must define an application area when you apply for research grants, so you need to state something. Nanotechnology is expensive and you thus have to become engaged in high value areas such as medico."

The medico focus is so strong that it is not contested. It is the routine focus of most Danish nano researchers, so certainly we are talking about strong attention rules here. Naturally, it is important in this respect that Denmark has a very strong medico industry that includes some of the biggest players in Danish industry.

Three other application areas are important, but they all spring from the same competence, catalysis. The core Danish competencies in this area mean that chemical production, hydrogen production and fuel cell research, and environmental catalysts (heterogeneous catalysis) are important research areas, particularly at the Technical University, Århus University and Risoe. At Risoe, the declared research strategy of the laboratory is energy production, so here most nano research is somehow related to energy production, e.g. new materials for windmill wings or organic solar cells. Even here, there is quite some medico-oriented research as well.

The research agendas are quite stable, not least because of money:

"We don't just pick up a new theme. You need a critical research group before you can start a new project" (researcher at iNANO).

The core Danish competency pointed to is clearly catalysis.

"Indisputably, we carry out outstanding research in the catalysis area. There is a fantastic dialogue between the research environments and the company Haldor Topsøe. Here, we have all the preconditions for being successful" (Professor Besenbacher, Head of iNANO).

Similarly, Professor Nørskov, Head of Nano•DTU states:

"We have succeeded in Denmark in making a really healthy combination of fundamental science and developing new products coupled to companies, especially Topsoe. Many countries would like to copy this Danish model; e.g. the US Department of Energy invited me over when they were going to develop a new strategy for their catalysis research. So I think we have a rather unique situation."

But expectations in the medico area are high, too. Professor Bjørnholm, Head of the Nano-Science Centre at the University of Copenhagen states:

"I believe that the biggest potential is in bio nanotechnology where we have a really good basis in Copenhagen. It is my and Tue Schwartz' [professor at the medical university in Copenhagen] vision that the platform created through biotechnology known as Medicon Valley in the Øresund [Baltic] region should be further developed with nanotechnology. In ten years we will have a strong nanotechnological medico hub here, probably the only one in northern Europe."

Also the field of energy technology is seen as a central, emerging competence within nano research in Denmark:

"Denmark has an outstanding position for contributing to the development of new nano-based technologies in connection with hydrogen as a fuel. The knowledge base at Nano•DTU and at Risoe is outstanding and several small and larger companies hold key positions in the field. This is true in hydrogen production where Topsøe are world leaders; it is true for fuel cells where Risoe, DTU, the companies Topsøe and IRD fuel cells and other players are strong in various subfields; and it holds in hydrogen storage. Here, DTU and Risoe are very active and where a new start up is just being created by Nano•DTU researchers. Nanotechnology is at the heart of hydrogen technologies since nanoparticles are the workhorses in all the energy conversion processes" says Jens Nørskov, Director of Nano•DTU.

In the suggested Nano Action Plan of the Danish Nano Foresight, seven high-priority areas within nanotechnology were identified (Ministry for Science, Technology and Innovation 2004). Within these areas, it is suggested that Denmark should build its core competencies in order to obtain a translation of nanoscience into industrial application, achieve increased growth and employment, and make solutions for important societal needs (in non-prioritized order):

- Nanomedicine and drug delivery
- Biocompatible materials
- Nanosensors and nanofluidics
- Plastic electronics
- Nanooptics and nanophotonics
- Nanocatalysis, hydrogen technology etc.
- Nano materials with new functional properties

Nanomedicine is the only application area highlighted; the other themes are more fundamental nanotechnologies that cover quite a broad spectrum of the nano-technological field. Environmental issues are not particularly addressed, but catalysis and hydrogen technology, existing strongholds, are.

Attention and perception of environmental issues

Core Danish competencies, those related to catalysis, are strongly related to environmental issues in the form of environmental catalysts for gas cleaning (heterogeneous catalysis). Haldor Topsøe holds 70 percent of the world market in this area. Given this core Danish competence, there is surprisingly little spread to other environmental areas in Danish nano research. There is in fact very little “environmental nanotechnology” (the term used by a researcher at the agricultural university) where environmental issues are defined as a target or application area for nano research. Clearly, the majority of the interviewed nano researchers had not or only vaguely considered the possible environmental applications or implications of their nano research.

The relationship between nano and environmental issues is seen as quite weak by the nano researchers.

“On the face of it there is only little overlap between environmental issues and what we do. Our work is very medico-oriented” (iNANO researcher).

Another iNANO researcher points to the lacking connections:

“I do not think the linkage is very strong. I have been in biology for many years and I have regarded the Ministry of the Environment as a closed system. It hasn’t been a part of my world. They have had their own agenda and have run this internally and financed their own institutions through all kinds of small technology programmes. For that reason my thoughts on the environment have not been directed towards that part of the environmental world. Of course, it has been part of the overall perspective, and an extra bonus, to make something environmentally friendly, but we have not directed our research towards the interaction with environmental companies or the ministry or anything like that".

The linkage between environmental researchers and the environmental industry and nano researchers is also quite weak; seemingly, there is a lack of attention both ways:

"The group of nano researchers is made up of molecular biologists, physicists and chemists. I think that the people who really work with environmental issues, e.g. waste water, have no knowledge of nanotechnology. That means that they can not see the opportunities in this technology. At some point when we get the nano ball rolling, they too will hear about nanotechnology, and I think the opportunities for cooperation will turn up at that point" (Professor Besenbacher, Head of iNANO).

An employee at the company Alfa Laval (that produces various membranes for handling pollutants) state that they do some nanotechnology, but they just do not call it that. They are interested in nanotechnology but have limited contact with the Danish nano researchers and follow biotech research more closely.

Professor Besenbacher, Head of iNANO, emphasizes the importance of maintaining a good nano image:

"When we start a new project the first thing we say is not: 'Now we are going to find a nano project which also has an environmental aspect'. It does not work that way. On the other hand, as we discussed the opportunities for the biosensor and oestrogen projects [directed towards curing cancer and hormone disturbances], I think I said that these themes were brilliant, because if we were to succeed with the projects there is no doubt that they would give us considerable PR. It would be something everybody can relate to."

For many catalysis researchers, the situation is quite different. They see a close linkage to environmental issues. For example, Ib Chorkendorff, Head of the ICAT (catalysis) centre, Nano•DTU, sees the environmental aspects of his catalysis research as a clear advantage.

"We seek solutions in technologies, and the environmental area is an area where everybody would like to see improvements. In that way, we are also opportunists. You have to find funding where it is, which is easier than if we researched an area without national industry and national interests."

The very strong Danish competencies on environmental issues in general and the strong competencies in catalysis might make us expect that Danish nano researchers were attentive to environmental issues and were working more broadly with them. But that is not the case. In fact, only a handful of Danish nano researchers do research aimed specifically at environmental issues other than heterogen catalysis and energy production. These researchers are typically on the periphery of the Danish nano research environment, i.e. not within the big new nano centres and mostly working only to a limited degree with nanoscience. They are situated at institutes working with environmental issues or areas related to them (e.g. the agricultural university and the building institute at the Technical University), where they apply nanoscience and nanotechnology in their research to some extent. There is also a niche at the Geological Institute at University of Copenhagen where a small group at the NanoGeoScience Centre works on environmental nano research, particularly waste and clean water issues. This group has links to environmental researchers at the agricultural university and the Technical University but only weak links to the Copenhagen Nano-Science Centre.

There are some nano researchers who are engaged in some (minor) environmental projects as a part of their research. There is also a large group, in fact a great amount of the research undertaken, whose research could have some or even major environmental impact but where this is not the focus or driver of the research undertaken; e.g. research into new lighter, stronger, or less energy demanding materials; or research into self-cleaning or anti-fouling surfaces; or research into detection of harmful substances. Section 5 on identified eco-opportunities highlights such research further.

To some degree, these researchers recognize the environmental potential of their research but mostly very vaguely and typically as something they are not used to consider. A researcher of composite nanopolymers, for example, which are very light strong materials (which could replace e.g. energy demanding or rare metals), states that he has a very pragmatic approach to his research and does not really know anything about the environmental potential (researcher at Ålborg University).

There are no specific environmental nano research programmes (again excluding heterogenic catalysis). There is no research that aims specifically to substitute hazardous, rare or energy intensive materials; or to build long-lasting products (self-repairing, anti-corrosive, hard etc.); Or to reduce resource consumption (through minituarization, targeted resource use and efficient chemical processes). All these issues, which are highlighted as environmental potentials of nanotechnology, are discussed in section 3.

The lack of environmental orientation was also evident in connection with the foresight project when finding speakers able and willing to talk about eco-opportunities related to nanotechnology for the innovation workshops and conference proved to be a problem. Obvious candidates were difficult to find, and many nano researchers were reluctant to address the environmental topic.

The general crude picture of green attention and search rules from the Danish investigation is that researchers at DTU, the agricultural university and Risoe are more environmentally oriented than at the pure and more basic research universities of Copenhagen, Aarhus, Ålborg, and the University of Southern Denmark. At the former, the medico orientation is less strong and the search space is broader. Also, at DTU, there are strong competencies on environmental issues and technologies, in part in some of the institutes dealing with nano research (the Centre for Sustainable and Green Chemistry at the Department of Chemistry, the IPL institute). These are both part of Nano•DTU, which to some degree facilitates cooperation between the technical environmental researchers and the nano researchers there. Apart from this, however, there are limited links between other core environmental researchers and the nano researchers. Risoe has a formal key research focus on renewable energy technologies, meaning that an environmental agenda is somewhat present.

All in all, it seems that links between policy makers, researchers and industry in the environmental area and the new main nano research centres are generally weak.

4.3 Environmental search rules and risks

Generally, most Danish nano researchers are concerned about the potential environmental risks related to nanotechnology. Concerns are predominantly directed towards and restricted to the possible toxicological effects of nanoparticles. There is clearly a concern that the public attitude towards nano may become negative, as in the case of GMOs, and that it is necessary to safeguard the reputation of nanotechnology.

A few researchers also point to a possible waste and recycling problem from nanotechnology. For example, a researcher from iNANO states:

“You put a lot of technology into a range of small things, and there may be a problem in collecting and recycling them again, like with rechargeable batteries. With nano products you can not see if there is anything dangerous in the pen when you throw it in the bin; you do not know what you are holding in your hand.”

The concerns of the Danish nano researchers are in line with recent international studies on nano environmental risks as discussed in section 3.

It seems that such risk concerns are quite new, or that they have at least been strengthened recently, partly because of the rising international debate resulting from recent research projects that go into more depth regarding risk aspects than had been the case before. But it also seems that the recent general Danish nano foresight report, which included risk aspects, has been an eye-opener to many Danish nano researchers when it comes to risks issues related to nanotechnology. In fact, this is one of the main conclusions of the foresight report. Before, the majority of the nano researchers had not been concerned with or considered risk aspects of nanotechnology (Ministry for Science, Technology and Innovation 2004).

A few nano researchers still state that they see no environmental risks associated with nanotechnology, but that there are some ethical issues to consider.

Even though risk aspects are recognized, little attention is generally paid to the question of how green/clean nano production is or could become, i.e. green search rules are either lacking or insufficient. Quite a few of the nano researchers interviewed lack competencies on environmental issues. They had difficulty discussing environmental issues in a systematic way and relating them to the product cycle, i.e. discussing resource and energy use, toxicity and waste and recycling aspects related to their nano research. For example, a researcher at the Copenhagen Nano-Science Centre states:

“Organic electronics is a huge area in rapid development and Denmark should get going here. But if it has got something to do with the environment… I don’t know if computers pollute?… An organic computer becomes CO2 and water. I guess computers belong at the bottom of environmentally pressing problems?”

All in all, there are no indications so far that the rise of nanoscience with its more transdisciplinary search rules nurtures any environmental orientation or competence building.

At Haldor Topsøe things are quite different. Keeping up a strong green profile is important to their competitiveness nowadays. They keep a close eye on developments in environmental regulation globally, especially on chemicals, both in order to spot market opportunities for their environmental catalysts, but also to handle the chemicals they themselves use properly. Their production nowadays is quite clean. They have e.g. a closed water circuit, but this has nothing to do with nanotechnology. They use hardly any catalysts in production themselves.[5]

There has been no Danish research into environmental impacts of nanotechnology.

An iNANO researcher points to the problem of timing the societal concerns and dialogues:

5 Interview with Frederik Søby and Søren Brun Hansen, Haldor Topsøe, 26/8 2004.

"It is difficult to research [in risks] because we have not defined the problems yet. We are all in the process of developing nanotechnology, and if it turns out that there are environmental consequences we must look into that; but it is difficult to start looking into things until you know what the problem is."

Similarly, Professor Besenbacher, Head of iNANO, states:

"I am more in line with the American way, and say: OK, we do this fundamental research and when it is done we draw a line in the sand and ask: what then, are there any side effects?… We need to investigate further the toxicological effects of especially the nanotubes, which may be dangerous. Today, we don't have sufficient scientific evidence to say whether it is dangerous or not. And that needs to be looked into, just as you do with heavy metals in paint… The day you see a problem, you have to direct regulation towards it. But I can't relate to an attitude saying that something as a starting point is a problem."

The committee behind the recently finished Danish nano foresight report held a small hearing with a group of citizens about their expectations and fears related to nanotechnology (Ministry for Science, Technology and Innovation 2004). The main conclusions were that there is a desire among the public wants nanotechnology to be used for purposes that give benefits with due regard for people and the environment. Examples include pollution control, climate change, poverty in developing countries, and disease. The responsibility for possible adverse consequences of nanotechnology and the applicable legislation for handling them must be precise and visible. It is important for applications that are evidently dangerous to be halted or subjected to regulation with strict toxicological control in order to maintain confidence that the widespread use of nanotechnology will not have undesirable consequences.

5 Danish Nano Eco-innovation potentials

This section seeks to outline the eco-innovation potentials identified by Danish nano researchers, both more generally and through 6 case studies.

5.1 Overall identified eco-potentials

When asked directly about nano-related eco-innovation potentials, the Danish nano researchers particularly pointed out three areas: 1) energy production (hydrogen society), 2) catalysis as a source of gas cleaning as well as resource and energy-efficient chemical production, and 3) sensors as a source of more resource-efficient production processes or products. Of the three, energy production was by far that to which most researchers attributed the greatest environmental impact, and also the issue they knew most about.

The overall impression is that all Danish nano researchers have some kind of – or even quite ambitious – green visions related to nanotechnology, but mostly at a quite general level. An iNANO researcher states:

"We need to scale things down to have enough resources when the Chinese start using computers, or else everything will break down. At the nanoscale, all processes are faster, also computer communication. The same goes for chemical reactions. Things become more efficient".

Most Danish researchers thus acknowledge various eco-innovation potentials related to nanotechnology and their own nano research, although very few actually research this aspect.

Table 2 below seeks in concentrated form to present a first mapping of all the eco-potentials identified by the actors in the Danish nano community. The table shows key emerging nanotechnological fields and their eco-potentials, as well as the main Danish nano researchers and companies involved. Also the development stage and Danish competencies (the international position) within the technology/research area are stated briefly.

Large parts of the Danish nano community have participated in making this table through several mailing rounds through which the matrix gradually grew and became more detailed and restructured. The matrix has also been presented as background material for the three workshops held as part of this foresight report. Thus, the findings have been subjected to some scrutiny within the nano community. Overall, the table represents quite rigorous data.

The table is quite long despite the limited attention to environmental issues in the Danish nano community. It should be stressed that the table is presenting eco-*potentials*, i.e. research that *could* lead to new environmental solutions, even though environmental applications may not be the target of the research or even considered yet. These issues are sought illustrated in the table by briefly indicating the current and potential application field of the technology. This is in some cases quite difficult since the field of application can be very broad or even undefined when dealing with a very fundamental technology as many of the nanotechnologial fields are (e.g. new nano-porous materials or new synthesis of nanoparticles). On the other hand, it is also important in a foresight exercise to try to point to the more long-term or novel possibilities, and not only those lying straight ahead or having obvious environmental potentials when considered in relation to the way we see environmental problems to day. Some more radical or systemic environmental opportunities may well lie in the more fundamental technologies or insights from nanoscience that may open up for new technological development paths.

Table 2 presents the eco-opportunities as identified by the Danish nano researchers. The claimed eco-potentials have not been subjected to great scrutiny in this project; the considerable number of suggestions alone makes this impossible. The purpose is not to identify those innovations with the highest environmental potential, but merely to make a first scoping study of the possibilities and visions. Table 2 may be said to express the nano researchers' entrepreneurial expectations for eco-innovations. For most of the nano researchers participating, considering the eco-opportunities of their research was clearly a new experience; therefore, it has also been difficult for them to be very specific about the environmental potentials of which they know little. The table therefore represents an attempt at identifying the hitherto unknown/unrecognized eco-opportunities as seen broadly in the Danish nano community. In a sense, this exercise has highlighted but also created new (eco-) entrepreneurial expectations, as did the innovation workshops held during this project. This then is a list of possible interesting eco-opportunities, not identified main solutions to specific environmental problems.

The grouping of the technologies made seeks simultaneously to capture:

- different application areas
- different nanotechnologies (manufacturing techniques)

- areas of environmental interest.

Minor sub-technologies are indicated with an "-". The grouping has been made in dialogue with the Danish nano researchers through the interactive mail survey.

The table very much illustrates the diversity of the nano-technological field and the great variety in the stages of development between the different research areas and technologies.

It goes beyond this study to enter a discussion of each of all the many technologies listed, their eco-potentials and industrial potentials. A few of the examples are discussed more in depth in the 6 case studies in the next section (marked with an "*" in Table 2).

Table 2. Suggested Danish nano eco-innovation potentials – overview.

Technologies & eco-potentials	Companies6	Researchers7
Catalytic production of chemicals:		
1.Efficient production of bulk chemicals such as ethanol, ammonium, hydrogen. Innovation for still higher energy efficiency and less chemical waste. Stage: Large-scale production New: micro-reactors for production of hazardous chemicals in small scale may allow more targeted, efficient production.	Haldor Topsøe	Ib Chorkendorff, Nano•DTU, DTU J. Kehlet Nørskov, Nano•DTU, DTU C. Hviid Christensen, Nano•DTU, DTU F. Besenbacher og Jeppe V. Lauritsen, INANO, AU Ulrich Quaade, Nano•DTU, DTU Jane Hvolbæk Larsen, Nano•DTU, DTU Ole Hansen, Nano•DTU, DTU, Mogens Mogensen, Risoe *DK: World leading (top 5)*.
Catalytic cleaning of gases:		
2. Environmental heterogeneous catalysts for power generation, refineries, large facilities (no catalysts for small facilities made in Denmark) Stage: Large-scale production, but more stringent environmental requirements are coming soon. New type of catalyst under development at Haldor Topsøe	Haldor Topsøe	I. Chorkendorff , Nano•DTU, DTU C. Hviid Christensen, Nano•DTU, DTU F. Besenbacher, iNANO,AU *DK: World leading (top 5)*.
3. Environmental catalysts for diesel cars* Heterogeneous catalysts for cleaning the fine (and toxic) particles of diesel engines. Stage: Development stage globally with	Haldor Topsøe Storex A/S Amminex A/S	C. Hviid Christensen, Nano•DTU, DTU J. Kehlet Nørskov, Nano•DTU, DTU Ulrich Quaade, Nano•DTU, DTU Tue Johannessen, Nano•DTU, DTU Jeppe Lauritsen, iNANO, AU Søren Linderoth, Risoe *DK: new area; Danish patents*

6 The companies are both Danish producers/developers as well as early users of nanotechnology. Companies in brackets imply a minor contact. A few foreign companies are mentioned when they have been in a dialogue with Danish nano researchers.

7 Abbreviations may be found in appendix 2.

new regulation coming up,		*and new products are on the way*.
4. Electrochemical/catalytic cleaning of gases Efficient cleaning method where electricity substitutes chemistry, application of know-how from fuel cells. Stage: Experimental, patent submitted.	Dinex Volvo	Mogens Mogensen, Risoe Kent Kammer Hansen, Risoe *DK: Unique research*.
Other separation/cleaning processes:		
5. Bioseparation - With ultrashort laser pulses, one can make membranes with nanopores in any material, including polymers and metals. These can be used for bio-separation or sensors. - Combination of membrane and fermentation processes - Bioactive polymer membranes No research/production in ceramic membranes for water cleaning. Stage: Used for gas cleaning mainly, on market within 5-10 years.	Versamatrix JURAG Alfa Laval Nakskov Danisco Christian Hansen	Bo Brummerstedt Iversen, iNANO, AU C. Hviid Christensen, Nano•DTU, DTU Morten Foss, iNANO, AU Peter Kingshott, Risoe Peter Vang Petersen, Risoe Gunnar Jonsson, Nano•DTU, DTU, Kemiteknik *DK: New area*.
6. Remediation with nanoparticles Immobilization and breakdown of pollutants. - Decontamination by reaction with functional nano particles or thin films - either using synthetic material or modified minerals. - Combined with sensors in e.g. the soil - Biological adhesion to natural materials and implications for degradation -"Natural attenuation": exploit the natural cleaning capacity of nanosize (clay and other minerals) particles in the soil. Application: In soil and water, water treatment facilities, waste treatment plants and storage areas, flue gas and fly ash treatment, nuclear waste repositories ect. Stage: Various – some projects improve existing commercial technology, others study the fundamental properties to develop new approaches.	Roskilde Amt Hedeselskabet SKB - Svensk Kärnebräslehantering	Susan Stipp, Geology, KU H. C. Bruun Hansen, KVL C. Bender Koch, KVL. K.J. Jørgensen, KVL H. Lindgreen, GEUS (C. Suhr Jacobsen, GEUS, F. Larsen, DTU & T. Christensen, DTU- environmental researchers with nano links) A. Bennow, KVL D. Plackett, Risoe *DK: Some projects are state-of-the-art, leading on international fronts*.
7. Controlled release into soil Controlled release of absorbed components from nanoparticles or films. Application: - Pesticides or plant nutrient or growth regulator release from soil, sediment. Aim: To improve resource efficiency and control release. Stage: Various		Susan Stipp, Geology, KU H. C. Bruun Hansen, KVL *DK: ?*
Polymer electronics/photonics:		
8. Polymer-based electronics with less use of materials and often less energy consumption. - TFT flat screen - Local Area Networks (LAN) - Molecular computing - RFID devices	Capres Atomistix SMB/MMP BioNanoPhotonics	M. Meedom Nielsen, Risoe Frederik Krebs, Risoe T. Bjørnholm, KU Jan. O. Jeppesen, SDU

Stage: Polymer electronics is beginning to be developed commercially; currently, products are too unstable. Many applications expected in a long-term horizon. Specific photonic applications are moving into development stage.		*DK: Early stage, for the time being a minor role, development in foreign countries: UK, USA, Asia, Phillips, Panasonic*.
9. LEDs * - Light emitting diodes with low energy consumption compared to incandescent bulbs and no environmentally harmful substances. Stage: Rapidly increasing performance of LED devices and expanding market globally.	RGB Lamps Nordlux Louis Poulsen Lighting Asger BC Lys NESA	Paul Michael Petersen, Risoe Carsten Dam-Hansen, Risoe Birgitte Thestrup, Risoe Henrik Pedersen, Risoe *DK: Development and test of high-end innovative applications of new LEDs*.
Monitoring & diagnosis:		
10. Lab on a chip Integrated and miniaturized systems for chemical analysis on a single chip. Measure at the nano-scale. Polymer-based fluid systems, photonics and electronics. Allows for decentralized, concentrated monitoring and diagnostics and thereby "early warning". - Pesticide analysis in drinking water (antibody- based), detection "lab on a chip" through quantitative, competitive microarray immunoassay. Stage: Chips for DNA analysis are well developed and applied (but are not quite lab on a chip). Mainly products within point-of-care in healthcare. Early production in food and environment.	Danfoss Analytical Exicon Novo Sophion T-Celic SMB SMB/MMP Danfoss Grundfos Coloplast	Pieter Telleman, MIC, Nano•DTU, DTU Leif Højslet Christensen, TI Knud Jørgen Jensen, KVL *Pesticide*: Jens Aamand, GEUS Leif Bruun, SSI Pieter Telleman, MIC, Nano•DTU, DTU *DK: Research and commercial production*.
11. "Pervasive sensoring" - Small cheap micro- and nano-structured sensors embodied in many different types of 'devices' (closely linked to regulation.) - Sensors based on RFID technology (tags for labelling) are expected to be largely disseminated. They are cheap, wireless and without internal energy supply (battery). The devices are disposable. Potentials for intelligent dosage systems (demand driven) & improved process control, e.g. combustion system in cars, dosage of fertilizers, washing machines, tags for waste separation (recycling) and discovering of materials… Application:: mainly health, automation Stage: Production of condition monitoring and structural health monitoring is increasing strongly. The durability of some products is short.	Danfoss Tempress H.F. Jensen Grundfos Unisense Unisensor Foss Analytics Dantec MEMSFLOW	Aric Menon, MIC/DTU Jörg Kutter & Jörg Hübner MIC, DTU Lars Lading, STC Steen Hanson, Risoe M. Meedom Nielsen, Risoe "Emballage & Transport" at TI establishing a RFID test centre. *DK: New area*.

12. Bio-sensors Monitors the presence of bio-chemical substances. The specification is achieved via a bio-chemical reaction. The devices are very small, sensitive and potentially cheap. The physical reading can be electrical, electro- mechanical, optical or ultrasonic. - Cellular sensor – the molecule changes its shape by binding - In-vivo nanosensors - Oestrogen receptors for detecting hormone-like compounds in the environment Application: mainly health, also food and environment Stage: Many proof-of-principle but still few commercial products. More robust sensors for routine measurements under development.	Chempaq Unisense Atonomics Vir Biosensors Radiometer DELTA Cantion, Sophion Danfoss Danfoss Bionics BioNanoPhotonics	Pieter Telleman, Nano•DTU, MIC, DTU Anja Boisen, Nano•DTU, MIC, DTU Erik V. Thomsen MIC, DTU T. Bjørnholm, KU & Tue Schwartz, Panum Jesper Wengel, SDU Jan. O. Jeppesen, SDU Steffen B. Petersen, AAU F. Besenbacher, iNANO AU Jørgen Kjems, iNANO,AU Jens Stougaard, AU N. Peter Revsbech, iNANO, AU Peter Andreasen, iNANO, AU L. Højslet Christensen, TI M. Palmgren, A. Schulz, A. Fuglsang, Knud J. Jensen, KVL Lars Lading, STC Niels Bent Larsen, Risoe A. Scharff Poulsen, Risoe K. Almdal, Risoe *DK: Research medium*.
Functional surfaces:		
13. Nano crystalline coatings Superhard nanocrystalline oxide or metal coatings with large thermal and chemical resistance Stage: Under development	Grundfos SCF Technologies	Jørgen Bøttiger (iNANO, AU), Ryzard Pyrz (iNANO, AAU) Bo Brummerstedt Iversen (iNANO, AU) *DK: Research in front*.
14. Multifunctional nanocoatings PLD (Pulsed laser deposition) is used to produce high quality films of nm-thickness. These are oxides and metal coatings with special electrical, magnetic and optical properties, e.g. for optical communication, sensor devices and SOFC (solid oxide fuel cells). Stage: Experimental prototype nanofilm systems, allows for fast production but currently too expensive for wider commercial use.		Jørgen Schou, Risoe Nini Pryds, Risoe *DK: Using new PLD equipment among European top ten*.
15. Coating surfaces with nanoparticles* - Anti-fouling, self cleaning surfaces, anti-bacterial surfaces Application: Mainly food and medico, some environmental, wide brainstorming stage concerning applications. E.g. environmentally friendly paint for ships, anti graffiti (avoid chemical usage for cleaning), self-cleaning windows (not DK) - Self-lubricating surfaces with reduced wear and tear, reducing problems with lubricants in industrial production. Potential for water/waste water, but no research in DK.	B&O (nano ph.d.) Grundfos Danfoss LEGO Danisco Mærsk Hempel	Per Møller, Nano•DTU, DTU Jens Ulstrup, Nano•DTU, DTU F. Besenbacher, iNANO, AU Thomas Zwieg, TI Peter Kingshott, Risoe Peter Bøggild MIC, Nano•DTU, DTU Hans Nørgaard Hansen, Nano•DTU, DTU Kim Dam-Johansen, DTU Jan Lorenzen, TI

Stage: Early production, larger production expected within 10-15 years.		*DK: Close to front*.
16. **Surfaces functionalized with complex carbon hydrates** -Bio-compatible surfaces, at present for medico technological applications -glyco-chip to gene discovery, enzyme and antibody screening **Stage**: ?	Danisco A/S Poalis A/S	Peter Ulvskuv (DIAS), KVL H. Vibe Scheller, A. Blennow ,S. B. Engelsen, B. Lindberg Møller, KVL Knud Jørgen Jensen, KVL Morten Foss & Flemming Besenbacher, iNANO, AU Leif Højslet, DTI Bill Willats, KU *DK: ?*
17. **Chemical modification of surfaces** - Plasma treatment, e.g. corrosion, biocompatible surfaces, (implants), adhesion, - Anti-fouling & antibacterial surfaces -Immobilized peptides, proteins, enzymes -Chemical synthesis of complex, bio-active molecules. - Coating with bio-layers Applications: consumer goods, automotive, health care **Stage**: Established industry. New coatings w. functionalized polymers, e.g. switchable coatings, expected time horizon 10-15 years to market.	SMB Nanon Coloplast	Anja Boisen & Martin Dufva MIC, Nano•DTU, DTU Morten Foss og Flemming Besenbacher, iNANO AU Niels Bent Larsen, Risoe Peter Kingshott, Risoe Jørgen Schou, Risoe C. Hviid Christensen, DTU Naseem Theilgaard, TI Knud Jørgen Jensen, KVL *DK: Medium level, many research activities in Denmark*.
18. **Physical modification of surfaces** Achieve strong surfaces (thermic stable, wearability), & anti-fouling properties. - Nanoporous membranes with selective permeability to short-chained carboxylic acid. Can be used for control of biogas plants, monitoring of fermentation in biotechnology. - Laser treatment - Replication of nano structures in metals and polymers. - Produce membranes (see bio-separation). **Stage:** Patents with external partners, on its way to be accepted by industry (food & medico). Within 2-5 years, larger market is expected.	Lego Glud & Marstrand Radiometer	Morten Foss, iNANO,AU Peter Balling, iNANO, AU Keld West, Risoe Niels Bent Larsen, Risoe Hans Nørgaard Hansen, Nano•DTU, DTU Anders Kristensen MIC, Nano•DTU, DTU Leif Højslet, TI Torben M. Hansen, TI, *DK close to front*.
19. **New Liquid Crystal Smart Window** Window for solar and daylight control applications, based on films of polymer-/liquid- crystal composites. Allows for higher energy efficiency though 3 operating modes: selective reflective (limiting overheating), transparent, and scattering. Fast response times independent of the glazing surface. **Stage:** Prototypes, estimated 5-7 years to market	European companies, no Danish companies	Karsten I. Jensen, Nano•DTU, BYG, DTU Finn H. Kristiansen, BYG.DTU Jørgen M. Schultz, BYG.DTU *DK: research into the metrology as part of EU project*.
20. **Intelligent windows/signs/boards** Coatings (with electro chromes) opens/shuts for the sun or change colour, allows for better energy efficiency. **Stage:** Development of energy-saving building components.	Velfac	Mogens Mogensen, Risoe Keld West, Risoe *DK: Early stage research, only little activity*.

21. Natural anti-fouling Use natural antibacterial agents for surface modification. Potentially saves chemicals and water for cleaning or for producing other coatings. **Stage:** Very early/infant, but not so far from market (5-10 years)	SMB	Peter Kingshott, Risoe Lone Gram, Institute for Fisheries. *DK: Among pioneers, also few other places, e.g. Australia*.
Composite materials: One of the two components contains structural modifications on nano scale.		
22. Fibre reinforced polymers - Plant fibres with nano-structured surfaces for improved interfaces in composites. - Polymer nanofibres (self-assembled and self-reinforced). - Nano components as sensors in composites. Eco-potential in light, thin, strong materials, e g. substitute glass fibre, steel and other metals, save energy use in transport. **Stage:** Long-term, 10-20 years to market.	NKT Flexibles Vestas NEG Micron LM Glasfiber	Anne Belinda Thomsen, Risoe Bent F. Sørensen, Risoe Bo Madsen, Risoe Hans Lilholt, Risoe Peter Kingshott, Risoe Henrik Myhre Jensen, AAU R. Pyrz, AAU Anja Boisen MIC, Nano•DTU, DTU Karsten Jakobsen, Nano•DTU, DTU Robert Feidenhans´l, KU *DK: in front*.
23. Super Insulating Aerogel Windows Nano-structured monolithic silica aerogel used as transparent insulation material in windows. Good optical and thermal properties of aerogel allows for windows with both high insulation and high transmittance. **Stage:** Prototypes, estimated time to market is 5-7 years.	European (e.g. Airglass, Sweden) (SCT Technologies)	Karsten I. Jensen, BYG.DTU Jørgen M. Schultz, BYG.DTU Finn H. Kristiansen, BYG.DTU *DK: Unique expertise in handling monolithic silica aerogel*.
24. Bioplast Polymer materials based on organic materials, permeability changes by addition of nano composites. Use of (nano) clay particles, sometimes in modified form. Is degradable, replaces fossil fuel resources of conventional plast. **Stage:** Early, some products are in production, but short durability. For bulk (packaging) as well as refined products.	Arla Foods	David Plackett, Risoe Vibeke Holm, KVL (ph.d.) Peter Ulvskov (DIAS), KVL H. Vibe Scheller, A. Blennow, S. Balling Engelsen (KVL) *DK: New nano research area*.
Nanoporous materials:		
25. Zeolites Development of organic/inorganic networks, metalphosphate lattice structure zeolites. Used for catalysis, gas storage, gas separation, chemical synthesis. **Stage:** Development. Zeolites are used in large quantities industrially. See also ”Gas storage”		Bo Brummerstedt Iversen, iNANO, AU Torben R. Jensen, iNANO, AU Jens E. Jørgensen, iNANO, AU Henrik Birkedal, iNANO, AU Hanne Lauritzen,TI Claus Hviid Christensen, Nano•DTU, DTU *DK: Research in front*.
26. Thermoelectric materials For cooling or energy production based on host/guest materials with nanovoids. **Stage:** Used today by NASA. New breakthrough may change cooling and/or energy conversion in a fundamental way.	Danfoss Grundfos SCF Technologies	Bo Brummerstedt Iversen, iNANO, AU Lasse Rosendahl, Energiteknik, AAU Georg Madsen, Kemi, AU *DK: Research in front*.

27. Nanoporous polymer materials Via self organisation at nano scala and corrosion creating a unique homogenous cavity structure. Application: potentially wide, e.g. membranes, electro osmotic pumps, controlled release and diagnosis. Stage: Early experimental		Sokol Ndoni, Risoe Martin E. Vigild, Nano•DTU, DTU *DK: Among pioneers, also 4-5 places in USA, Japan*.
28. Super vacuum insulation Coal doped nanostructured aerogel used as spacers for vacuum insulation panels. Application: In refrigerators, freezers, coolers, as building insulation etc. Other applications of aerogel: - Substrate for catalytic materials, - Gas filters, - Waste encapsulation and membranes etc. Stage: Vision/possible project idea and reasonable price.		Karsten I. Jensen, Nano•DTU, BYG. DTU Jørgen M. Schultz, BYG.DTU Finn H. Kristiansen, BYG.DTU *DK: New area, participates in EU project*.
29. Ceramic insolation Ceramic nanoporous tiles (ceramic processing) for high insolation capacity. Stage: expensive, used in Space shuttles, vision/potential research idea.		Mogens Mogensen, Risoe *DK: No research so far*.
Nanoparticulate & nanofibrous materials:		
30. Nanoparticles formed into meshes, wires or colloid 3D constructs. Aimed at medico (transport & penetration, increase surface area) but wide application potential, e.g. as scavengers of pollutants, flocculation. Stage: Experimental		Sokol Ndoni, Risoe T. Bjørnholm, KU Peter Kingshott, Risoe Keld West, Risoe B. Lindberg Møller, KVL *DK: Among early pioneers*.
31. Supercritical fluids Synthesis of nanoparticles in any form and shape, e.g. TiO_2, ZrO_2, Al_2O_3, Fe_2O_3. Green synthesis without using organic solvents. Extraction processes: Conversion of slurry to H_2 and CH_4. Stage: Commercially available today	Grundfos SCF Technologies	Bo Brummerstedt Iversen, iNANO, AU Torben R. Jensen, iNANO, AU Jens E. Jørgensen, iNANO, AU *DK: New area*.
32. Synthesis of nanoparticles * Hydrothermal and supercritical synthesis of e.g. complex oxides, magnetic particles etc. for much faster and more energy-efficient synthesis of nanoparticles. Stage: Used commercially today (fuel cells, solar cells, catalyst supports, electronics etc.). Improvement of size distribution and price may create a burst in commercial exploitation.	Grundfos SCF Technologies	Bo Brummerstedt Iversen, iNANO, AU Torben R. Jensen, iNANO, AU Jens E. Jørgensen, iNANO, AU Henrik Birkedal, iNANO, AU C. Hviid Christensen, DTU *DK: New research and production area with promising new unique production facility*.
33. Biomimetic materials Develop new materials based on the study of fundamental mechanisms of biomineralisation. Stage: ?.		Susan Stipp, Geology, KU Karen Henriksen, Geology, KU (ph.d. student) *DK: ?*.

Energy production:		
34. Energy conversion Micro-/nano-structured fuel injectors for combustion engines. Injectors manufactured using ultrashort laser pulses enables improved atomization, which ensures improved combustion of e.g. diesel. Stage: ?.	Bosch GmbH	Peter Balling, iNANO, AU *DK: New area*.
35. Hydrogen production & fuel cells/bio- fuels - Hydrogen production - Hydrogen storage in nanoporous materials (metal hydrides) - Cheap materials for electrodes (nano-structured) Stage: Early production	Haldor Topsøe IRD Fuelcells	J. Kehlet Nørskov, Nano•DTU, DTU I. Chorkendorff, Nano•DTU, DTU C. Hviid Christensen, Nano•DTU, DTU Mogens Mogensen, Risoe Søren Linderoth, Risor R. Feidenhans'l, KU F. Besenbacher, iNANO, AU Frank Elefsen, TI, *DK: New area but approaching international front.*
36. Gas storage Synthesis of complex metal hydrides promising for H_2 storage and thus hydrogen fuel and nanoporous organic networks. Stage: Early development		Torben R. Jensen, iNANO, AU Bo Brummerstedt Iversen, iNANO, AU Jens E. Jørgensen, iNANO, AU C. Hviid Christensen, Nano•DTU, DTU *DK: New area*.
37. Polymer solar cells Very cheap solar cells printed on thin plastic films, potential for wide distribution of solar cells, e.g. integrated in products. Stage: Experimental, short durability but rapid development. First products expected soon.	Siemens	Frederik Krebs, Risoe *DK: New area*.
38. CO_2 sequestration Development of risk assessment models for storage of CO_2 in exhausted oil/gas reservoirs. Based on study of fundamental nano-level processes for mineral-gas and mineral-liquid-gas interaction. Stage: ?		Susan Stipp, Geology, KU *DK: New area, project with European partners.*
Atmospheric research:		
39. Nanoscience research into ozone layer and global heating. Stage: Probably not technically relevant		Ole John Nielsen & Merete Bilde, KU

5.2 Eco-potential qualification

The main conclusion of Table 2 is that Danish nano researchers identify a very wide range of emerging nanotechnological fields with direct and indirect eco-potentials. Many of these potentials have also been pointed to in previous studies and workshops (compare the discussion in section 3 on international findings). But Table 2 offers a more comprehensive list with more details related to concrete research areas and (upcoming) technologies than has been carried out before.

It should be remembered that the list reflects the Danish identified potentials and refers to Danish nano competencies only. In other countries, the picture may look different. There is e.g. no photocatalytic research for water cleaning in Denmark, which is often highlighted as one of the big eco-potentials of nanotechnology.

The technologies pointed to indicate in general that there are some intrinsic features of nanotechnologies that may facilitate eco-innovation within a wide diversity of nanotechnologies, as others also have argued (compare section 3).

The table operates with eleven different main research /technology areas and identifies a total of 39 research areas/technologies which could offer eco-potentials. These can be further grouped into four main groups, representing different ways of contributing with environmental benefits. 1) The table illustrates numerous examples of how nanotechnologies imply new opportunities for making more tailor-made, targeted, sensitive, integrated and intelligent products - in short, smart tailored products. 2) Combined with the opportunities nanotechnology offers for making completely new materials that are thinner, lighter and stronger, or possess new properties, nanotechnology may well provide a platform for a more resource-efficient economy. 3) Finally, energy production must be mentioned as the third area, and 4) improved environmental remediation and cleaning as the fourth area where nanotechnologies may have considerable positive environmental impact. These are discussed further below.

This is not to claim the mentioned nanotechnologies are resource efficient per se and will solve the environmental problems if widely developed. The environmental benefits depend very much on how the technologies are being developed and applied, and how they feed into and possibly affect overall consumption patterns. Currently, most of these research areas and technologies are not being developed with environmental benefits in mind in Denmark, so the eco-potentials are likely not to be explored to a very large extent.

Lacking knowledge of many of the research/technology areas, means that the specific environmental benefits are difficult to assess, particularly considering the broad application area of most nanotechnologies. Because nanotechnologies are enabling technologies, many of the environmental effects will be widespread but of a more indirect character. They will often be integrated in (and thereby change the properties of) other products and materials and their effect must be seen in combination with these. In the following, the eco-potentials are discussed in more depth, with references to the box numbers in Table 2.

Add. 1 Smart tailored products

The eco-potential of smart tailored products relate, roughly speaking, to the following research areas:

- Functional surfaces (making strong, self-repairing, anti-fouling, self-lubricating, bio-compatible, energy-preserving/-producing, selective surfaces).
- Catalytic efficient production of chemicals (less energy and waste)
- Polymer electronics/photonics (particularly less energy)
- Monitoring and diagnostics (e.g. pervasive, highly sensitive sensoring and tags – based on cheap, disposable, organic electronics and bio-sensors).

Functional surfaces alone are represented by nine very different technologies, some at a commercial stage, some very experimental. Quite a few Danish nano researchers are occupied with this very fundamental nanoscience discipline, where Denmark possesses quite strong competencies. Company involvement is, however, somewhat limited so far. The eco-potentials are considerable because of the potential widespread and varied application, although application today is primarily medico-oriented. There are a few examples of current commercial environmental applications with self lubricating surfaces used in industrial production to save resources (see no.15), energy-efficient windows through nanocoatings (see nos. 19 and 20) as well as three examples leading to less chemical and water usage in the case discussed in the next section.

Catalysis, the core Danish nanotechnological competence, leads to more resource-efficient chemical production as will be discussed further below. *Polymer electronics/photonics* represent radical innovations in the electronics industry, which is crucial for the global economy. Polymer electronics is a small new niche in Denmark as well as globally with interesting perspectives and some industrial activity. Although some commercial products do exist, considerable technical problems remain. The eco-potentials may be considerable, because radically new types of electronic products may be developed. In most cases, polymer electronics offer environmental benefits mainly in the form of energy efficiency; see especially the LED case below (no.9), possibly one of the nanotechnologies with the biggest immediate environmental potential. *Monitoring and diagnostics* represent one of the biggest nano research areas in Denmark when it comes to numbers of researchers, and it is also here we find most nano-dedicated companies, primarily small start-up companies. The identified technologies (pervasive sensoring with sensors and tags, lab-on-a-chip and bio-sensors, see nos. 10-12) might facilitate continuous and real-time measurement and diagnosis of environmental parameters in a way that has not been possible before. The environmental potential of this element alone may be contested, but used in combination with other intelligent (nano) products and materials it may contribute in important ways to greater resource efficiency. The application orientation today is, however, primarily medical. There is though an example of sensors for pesticide detection (see no. 10). The environmental monitoring industry in Denmark is only beginning to take an interest in nanotechnology.[8]

Add.2 New materials

According to professor Hviid Christensen, Centre for Sustainable and Green Chemistry, DTU, who is among the environmentally most competent nano researchers in Denmark, the biggest eco-potential of nanotechnologies lies in the possibility of making completely new nano-structured materials. All modern materials science today is based on

8 Interview with Kasper Paasch, Danfoss Analytical, 7.9.2004.

nanoscience, so in this sense the innovation potential attributed to nanotechnology is considerable.[9] The three material areas in the table are:

- Nano-particulate and nano-fibrous materials (eco-efficient production and materials with new properties)
- Nano-porous materials – (potential for membranes, electro-osmotic pumps, controlled release, insulation, thermoelectric materials for efficient cooling and energy production)
- Nano composites (lighter, stronger, degradable, renewable raw materials…)

The nano-particulate and nano-fibrous materials group illustrates some of the most fundamental nano-science research and development. They feed into a great amount of nanotechnologies. Basically, the further development of many nanotechnologies depends on the advancements in the ability to make efficient nanoparticles. The importance of this field underlines the necessity to look into the entire innovation food chain of nanotechnologies to enhance nano innovation. Improved synthesis of nanoparticles (see nos. 31 and 32) and forming nanoparticles into meshes, wires or colloid constructs to obtain materials with new properties (see no. 30) illustrate this point. A case in the section below on new super-critical nanoparticle synthesis shows considerable improvements in energy efficiency, speed and quality of the manufacturing technique compared to the much slower sol-gel method practiced previously. The company involved (SCF Technologies) is the only Danish company working with the manufacturing of nanoparticles. Also bio-mimetic materials (no.33) represent an interesting potential for making completely new materials that mimic the efficient production methods of nature.

Nano-porous materials also make up a very important and fundamental element of nanotechnologies and are used in a range of nanotechnological devices. This nano research strives basically to make homogenous nano-scale holes in a material. The table illustrates five different ways that give rise to very different material properties and a wide range of application areas. The eco-potentials are considerable, e.g. improved membranes and better catalysis and novel solutions for insulation, cooling and energy conversion (nos. 25, 26, 27, 28 and 29). Some of these applications are commercial, others experimental and currently very costly, but they could have major eco-potentials if they achieve commercialization.

Within composite materials research, the nano research related to the development of bioplast is one rare example where environmental aspects form an important part of the goals and search rules. The whole justification of bioplast is based on environmental issues, in the search for plastic with less waste problems and based on renewable resources but using biomass. Bioplast research in Denmark is only a small niche however. Nano-composite materials such as fibre reinforced polymers are generally very interesting from an environmental point of view, because they make up lighter, thinner and stronger alternative materials to e.g. steel and other metals to be used e.g. in transport to save energy and material use, as pointed out in section 3. This research, however, has limited environmental application today in Denmark. An exception is research and development into composites for the replacement of glass fibre in windmills, partly to develop better wings, partly to reduce the huge glass fibre waste problem of the big Danish windmill industry.

9 Acccording to Hans Lilholt, program leader of the materials division, Risoe National Laboratory.

Add. 3 Energy production

As mentioned, the Danish nano researchers point to energy production as a core eco-potential of nanotechnologies. Certainly, if alternative energy systems for fossil fuels were developed, a great many environmental problems would be solved. The strong Danish catalysis competencies provide a good basis for contributing to the development of hydrogen-based energy systems. Interestingly, the Danish catalyst researchers have all moved into the related hydrogen fuel cell and storage research within recent years, both at DTU, iNANO and Risoe, and also at Haldor Topsoe. There seems to be a shared long-term interest in realizing a hydrogen economy in which possible environmental benefits play an important role. The technical problems remain considerable, however, and prospects are long term and uncertain. The catalysis case below illustrates recent innovations here. Other potentials within the energy area are improvements in energy conversion, the mentioned improved materials for windmill wings and an interesting new niche in polymer-based solar cells. The latter is an example of a nanotechnology at a very early experimental stage, but which could have a huge innovation and eco-innovation potential if commercialization is realized. The high uncertainty as to the scope of this technology makes it very difficult at present to assess possible environmental benefits.

Add. 4 Environmental remediation

This area represents what professor Hans Christian Bruun Hansen at the agricultural university calls "environmental nanotechnology", where nanotechnology is used directly to reduce the amount and handling of pollutants. The techniques pointed to are catalytic efficient cleaning of gases (nos. 2,3,4), remediation through use of functional nanoparticles (no. 6), more efficient bio-separation (no. 5) through tailored membranes, and controlled release of e.g. pesticides, nutrients and growth regulators into the soil (less resource use and emission, no.7). The latter shows how understandings of nanoscale processes in the soil may be used to find novel environmental solutions.

The most novel suggestion is the use of functional nanoparticles (no. 7, synthetic particles or modified minerals) for binding and degrading pollutants in soil and water, waterworks, waste treatment facilities, nuclear waste storage areas etc. Such technologies are to a limited degree already in use (see the case below on "Nat-nano-mats"). Here, the importance of new, nanoscience-based understanding (rather than devices) of vital nanoscale processes in the environment are emphasized for finding optimum solutions to environmental problems and the construction of risk assessment models (according to Susan Stipp, GeoNanoScience Centre, University of Copenhagen).

The Danish core environmental competence within heterogeneous environmental catalysis distinguishes itself as a well-established technology (no. 2). In the western world, existing heterogeneous catalysts are already generally well applied. A researcher at Haldor Topsøe states: "I don't think there is any material today which you cannot remove one way or the other, but there are still many regions where it could take place. It is a question of the will to implement the existing processes where the problems are".[10]

At Haldor Topsøe, they see the biggest remaining eco-potential in spreading the environmental catalysts to Asia, Eastern Europe and the rest of the developing world, where huge markets for environmental technologies are developing. In these regions, environmental catalysts now have only limited application. At Haldor Topsøe, they do not ex-

10 Interview with Frederik Søby, Haldor Topsøe, 26/8 2004.

pect major innovations in the environmental catalysts originating from the new, more scientific (nano) understanding, but rather smoother developments with continuous increases in efficiency. The same goes for the catalysts used in chemical production, where innovations lead to still less energy use and less chemical waste (compare the resource efficiency discussion above in relation to smart products, no. 1). They are still facing challenges connected with linking up the traditional experiment-based production at the production facilities and the nanoscience research at their R&D department. Since stricter up-coming regulation of sulphur emissions will mean that major innovations in their environmental catalysts will be necessary, they are working towards this.

The catalysis competencies are recently being applied in new directions (see also the hydrogen discussion in the energy paragraph). Catalyst researchers at both DTU and Haldor Topsøe are now moving into diesel cleaning, where new regulation is coming up (see no. 3). For Haldor Topsøe, this is quite a new strategy, since the mobility sector is a completely new type of market (much smaller users); they hitherto specialize in big users. See also the diesel/hydrogen case below, where Haldor Topsøe is not involved however. New research is also going on within electrochemical cleaning of gases, where electricity replaces chemicals (no. 4).

The six case studies in the following section represent examples of a more detailed discussion of both innovation opportunities and environmental impacts.

5.3 Cases on nano eco-potentials

Based on input from a number of Danish nano researchers, six case studies are presented to illustrate the innovation and environmental potentials in more detail. These can be used for a more specific environmental assessment, since more is known about the specific potential application areas and production techniques. A brief environmental assessment is made of each case by Stig Olsen, IPU, with a balanced evaluation of environmental benefits as well as possible threats.

The cases are chosen in order to illustrate different kinds of nanotechnologies and how they can offer different types of solutions to environmental problems. They are examples of more mature nanotechnologies with products already on the market. Hence, the cases also seek to illustrate interesting Danish innovation activities. The cases have rather clear environmental advantages, but this does not mean that these are innovations with the highest eco-potentials.

Case: Super-critical synthesis of nanoparticles[11] – innovation in nano manufacturing (no.32)

Nano materials are cornerstones in many attempts to develop and exploit nanotechnology. Numerous new applications are being developed, including electronics, sensors, coatings, optical fibres/barriers, ferro fluids, ceramics, membranes, catalysts, paints, lubricants, pesticides, food additives, anti-microbials, sunscreens, fuel cells, solar cells, cosmetics etc. In virtually all applications of nano materials, it is the primary synthesis of the materials that limits further exploitation of nanotechnologies. It is essential to focus on new processing technologies if nano materials are to become competitive in the market.

11 Data for this case was provided by Professor Bo Brummerstedt Iversen from iNANO at Aarhus University.

Super-critical synthesis processes comprise sustainable green chemistry routes as the reaction media, e.g. environmentally benign CO_2 or H_2O in the super-critical state. Compared with the present state-of-the-art in producing nano materials, super-critical processes allow production at significantly lower temperatures and shorter reaction times than conventional methods, and the need for subsequent drying and/or calcination is eliminated. The super-critical preparative schemes hold great promise for revolutionizing the quality and availability (reduced cost, easier processes, improved homogeneity) of modern nano materials. Whereas conventional sol-gel methods may take hours, the super-critical methods are finished within less than a minute.

There have been tremendous advances in super-critical fluid technology in the last decade. Today, traditional applications in extraction processes (e.g. caffeine from coffee) have been augmented by applications in e.g. materials processing, organic reactions, separations, polymers, pharmaceuticals etc. Danish applications with environmental implications include wood treatment (the brand name "Superwood") or water treatment, and conversion of organic waste to hydrogen, methane and bio-diesel. Super-critical fluids exhibit unique properties such as gas-like mass transfer properties (diffusivity, viscosity and surface tension), yet have liquid-like properties such as high solvency capability and density. Furthermore, solubility can be manipulated by simple means such as pressure and temperature.

Together with the Danish company SCF Technologies, iNANO has recently developed a unique multipurpose, continuous flow, super-critical synthesis reactor capable of producing extremely homogenous nanoparticles. The system, which can handle all common super-critical solvents, allows easy scaling to industrial production. The flexible design allows synthesis of most materials, which are otherwise fabricated by sol-gel or hydrothermal methods.

Environmental assessment

Compared to the processes normally used in nanoparticle production using traditional production methodologies, as listed in Table 2, the super-critical synthesis of nanoparticles will undoubtedly present an environmental advantage, even though the alternative sol-gel process is not one of the most energy consuming processes. With regard to raw materials, super-critical synthesis may potentially be able to use raw materials that are less processed. No differences are expected in the use and disposal stage of the nanoparticles. The most significant difference will probably exist in the processing of the nanoparticles. First of all, the super-critical synthesis of nanoparticles is likely to reduce both time and costs and improve the homogeneity of the nanoparticles, which may lead to a larger use of nanoparticles. Depending on the properties and use of the particular nanoparticle (e.g. as shown in Table 2), this may lead to either environmental benefits or increased risks.

Case: Nano-technological coatings based on sol-gel synthesis[12] - innovating surfaces

A newly developed type of chemically synthesized hybrid coatings produced by means of the so-called sol-gel technology (sol as in solution and gel as in gelatine), also characterized as chemical nanotechnology, has revolutionized the opportunities for altering the surface properties of a large series of materials, including nearly all metals and alloys,

12 Data for this case has been provided by Thomas Zwieg, Danish Technological Institute, Aarhus.

glass, wood etc., by the formation of a strongly connected inorganic, ceramic network combined with organic chemistry's ability to introduce various functionalities.

The sol-gel technology is based on the polymerizing of small inorganic molecules; in a simple instance, metal alkoxides $M(OR)_n$ are being used. In these cases, the metal, M, represents silicon, titanium, zirconium, aluminium etc., and R presents an alkyl group, typically methyl or ethyl. Through hydrolysis and a subsequent condensation reaction, it is possible to cross-link the molecules into a metal-oxopolymer nanoparticle 1-50 nm in size. These nanoparticles constitute a basis for producing thin ceramic coatings, ceramic phases or porous structures.

During the last couple of years, research and development within chemical synthesis has resulted in an overwhelming number of commercially available metal organic chemicals, which makes it possible to introduce different organic groups in covalent connection with this inorganic network. By introducing such organically modified metal alkoxides into the formation of the before-mentioned nanoparticles, the backbone of the ceramic coatings can be enriched with a chosen functionality. Thus, it will be possible to modify the physical, chemical, optical and mechanical properties of the formed coatings or structures to an extent that cannot be achieved by conventional methods.

Within the last couple of years, the Danish Technological Institute has experienced great success in producing sol-gel coatings with emphasis on specific functions, i.e. limestone repellence on metal surfaces, ice repellent properties for application in the aircraft and windmill industries and anti-graffiti lacquer for the train industry, for instance. For the anti-limestone and anti-ice coatings the adhesion of the respective crystals is so minimal that a slight dynamic influence – for example, the flow of water or air – is sufficient to clean the surface. Therefore, a large saving in the application of materials to remove chemical ice and limestone can be expected. The use of chemical nanotechnology for the development of the new type of anti-graffiti makes it possible to remove graffiti vandalism on prepared surfaces with just water rather than the chemical solvents that have been used up to now.

The experiences obtained in these projects have justified the expectation of successful application of sol-gel technology for the production of a non-poisonous, anti-fouling coating intended for boats. With support from the Danish Ministry of the Environment, a craft project for the purpose of testing some selected sol-gel lacquers was completed in 2004. In co-operation with three yacht clubs, the lacquers were applied to a number of test plates and private boats and tested throughout the yachting season. The most important results obtained from this project include a visible reduction of alga growth and a considerably easier ability to clean the boats at the end of the season.

Environmental assessment

The nano-technological coatings described can to a wide extent be expected to substitute other ways of providing functions such as de-icing, antifouling etc. Thus, the development is not expected to create new needs.

De-icing is currently performed using different types of organic solvents, mostly glycols, and using a nano-technological coating might be able to substitute this use. The same applies to anti-graffiti. It is not known as yet how much of a coating will be required, how long it will last and whether components of the coating will be released over time. It also remains to be seen what the possible effect of such a release would be.

Antifouling is normally performed with rather toxic compounds such as organotin compounds, which cause impacts in the marine environment, especially in harbours. A substitution of these by non-hazardous alternatives would clearly be an environmental benefit if the nano-technological coating does not release other similarly hazardous compounds during use.

In a LCA comparison between a nano-technological varnish and three conventional varnishes (water based, solvent based and powder), the nano-technological varnish was clearly environmentally better in terms of the amount of material used and emissions (VOC and others) during the life cycle, partly because it was possible to obtain the same properties by applying thinner layers of coating (Steinfeldt et al. 2004).

Producing nano material via the sol-gel production process is not expected to be very different from other types of chemical processing.

Case: LEDs for eco-innovation in lightning[13] - high-end applications of nanotechnology

LEDs is one of the areas frequently highlighted when referring to the eco-potentials of nanotechnology.[14] Commercial Light Emitting Diodes (LEDs) are in a rapid stage of development globally. The light emission is now so strong that LEDs can be used for general illumination. The successful application of LEDs in general illumination is forecasted to provide significant economic and environmental benefits. Today, LEDs can be found in many applications requiring coloured light, such as signs, traffic signals and automobile brake lights. Recent advances in nanotechnology, compound semiconductor materials and enhanced manufacturing techniques are enabling a new generation of blue, green and white LEDs. White LEDs are based on a blue LED that is used to pump a mixture of phosphors in order to produce white light. White LEDs can, however, also be achieved by mixing light from multiple LEDs of different colours. The latter method, known as RGB-technology, is a new technology being developed in Denmark. This technology has potentially higher energy efficiency and the advantage of colour tuneability that leads to flexible lighting sources.

The advantages of LEDs are many, such as low maintenance cost, tuneability and compact size, but also environmentally important factors such as longevity, energy efficiency and no environmentally harmful substances. In the user phase, energy consumption is low compared to incandescent bulbs, leading to SO^2 reductions etc. LEDs need only about 50 percent of the power required by a normal bulb in order to produce the same amount of light.[15] The longevity in the user phase means a considerably reduced production of light sources (replacing 50-100 incandescent bulbs with low longevity). LEDs are also environmentally friendly in the waste phase, as the content of heavy metals is small (e.g. no mercury, no UV-light) compared to fluorescent lamps. Since LEDs can now produce high quality white light and can thus be expected to replace conventional lighting technology, such a switch would result in substantial energy savings. Recent estimates suggest that under the U.S. Department of Energy’s (DOE) accelerated schedule, solid-state lighting could displace general illumination light sources such as incandescent and fluorescent lamps by 2025, decreasing energy consumption for lighting by 29 per-

13 Data for this case is provided by Carsten Dam-Hansen and Paul Michael Petersen, Risoe National Laboratory and Jørn Scharling Holm, NESA.

14 European Commission (2004). Nanotechnology. Innovation for tomorrow’s world.

15 European Commission (2004). Nanotechnology. Innovation for tomorrow’s world.

cent and saving 3.5 quadrillion BTUs[16]. In Europe, about 10 percent of the electrical power produced is used for lighting; in Denmark, the figure is 12 percent.

Commercial LEDs have reached and surpassed the energy efficiency of incandescent lamps with a luminous efficacy of 60 lumens/Watt for red LEDs and approx. 20-40 lumens/Watt for white LEDs. Red LEDs have reached 100 lumens/Watt in laboratories, and with future improved LED materials, luminous efficacy is expected to reach 150 lumens/Watt. Thus, LEDs are expected to challenge the energy efficiency of fluorescent lamps in the future.

Nanotechnology plays a major part in the development of new enhanced LEDs, with higher energy efficiency but also higher total luminous flux. (The total luminous flux from a single LED package is so low today that only low wattage incandescent lamps are readily replaced by SSL sources.). Novel growth technologies using nano-scale patterning are employed for improved substrates and precise layering of semiconductor materials. Quantum-dot heterostructure LEDs with structure sizes around 10 nm are utilized for high efficiency light generation. Nano-composite LED die/chip encapsulants with high refractive index are being developed for improved light extraction from the LED chip. Quantum-dot structures in the encapsulant material can emit visible light when excited by a UV LED and may thus be used as nanophosphor, an alternative to using yellow phosphors for white light generation. This may result in new ways to tune the spectrum of emitted white light.

LED technology development is taking place globally, driven mainly by large companies in the US, Japan and Germany, and research institutes like Sandia National Laboratories.

In Denmark, development of a niche is sought, directed not so much towards components but towards novel high-end applications of high brightness LEDs for general illumination. An ongoing project aims at developing a high quality LED lamp based on RGB-technology, with high colour rendering and tuneability to replace low wattage incandescent lamps. Novel micro- and nano-structured optical elements are being developed for efficient colour mixing and light control. The project is a cooperation between Risoe National Laboratory and Danish industrial partners, NESA, RGB-Lamps and Nordlux. A new project starting 2005 continues and extends this work, aiming to develop novel types of fixtures and lamps for this new generation of innovative and flexible form of illumination. This is being done in cooperation with Asger BC Lys and Louis Poulsen Lighting. Both projects are supported by ELFOR, Dansk Eldistribution.

Environmental assessment

Lighting is a heavy energy user, 10-12 percent of electricity consumption, so reductions here have major environmental impact. Since lighting is widely used both in public and private spaces, it is not likely that the development of new types of lighting such as LEDs will extend the use of lighting considerably. Thus, it is expected that LEDs will substitute other types of lamps rather than create new needs. In the use phase, the development of LEDs that are more energy-efficient will provide an environmental benefit. An incandescent lamp has an efficiency of approximately 5-12 lm/W, whereas it is foreseen that efficiencies of 150 lm/W may be obtained by LEDs. But already now, LEDs with efficiencies of 20-60 lm/w are more efficient than incandescent lamps. However,

16 Source: http://www.sandia.gov/lighting/

the now widely used fluorescent lamps still have higher energy efficiencies (50-75 lm/W) than LEDs.

With regard to the materials used for producing the different types of lamps, LEDs have an advantage in comparison with fluorescent lamps, since no mercury is used in LEDs. It can also be expected that the material amounts will be less for LEDs. During production of LEDs, it can be expected that the energy requirements are high, since the nano materials used will probably be produced by vapour phase deposition or lithography, both processes that require clean room facilities (see Table 2). During disposal, fluorescent lamps are collected as hazardous waste, thereby securing collection and reuse of mercury and other materials. This is not the case for incandescent lamps and probably not for LEDs. For LEDs, the reuse of nano-materials may constitute a problem.

The future practical application of quantum dots will most certainly lead to a further increase in energy efficiency within light sources. It is anticipated that quantum dot technologies will find their place in display technology, especially in combination with OLEDs (organic LEDs). It will take a few more years, however, until quantum dots achieve a position as commercially viable products (Steinfeldt et al. 2004).

Nat-nano-mats – Natural nano materials for treating water, immobilizing waste, or dosing pesticides and fertilizers[17] *- Innovation for environmental remediation*

Insuring clean water, dealing with waste, and producing food are some of the most critical issues of sustainability for human existence as well as for a secure environment for plant and animal species. Often, in our attempts to solve one pollution problem, we create one or several more. Strategies that make use of natural processes on natural materials are one way of minimizing adverse anthropogenic effects.

Nano materials have been around in nature since the beginning of time. Mineral particles, macromolecules and coatings only a few atomic layers thick have always controlled the composition of water, whether in rivers, lakes or oceans, in soil or hydrothermal systems. Reactions at the interface between natural solids and fluids have always been responsible for uptake and release of trace components that can either be essential for life or toxic. With the birth of nanotechnology, tools became available that enable geoscientists to directly observe these processes; their work has entered a new realm. There are three aspects of 'nano' – nanometrology (the development of instruments and methods for observing samples), nanoscience (the definition of physical and chemical processes at the nanometer scale), and nanotechnology (the development of devices and advanced materials for solving specific problems). The development of a saleable product, including those relevant for environmental protection, requires progression in that order. The application of nano techniques to environmental questions is still in its infancy, but a good start has been made.

17 Data for this case has been provided by Susan L. Svane Stipp, NanoGeoScience Group, Geological Institute, University of Copenhagen, Hans Christian Bruun Hansen and Christian Bender Koch, Environmental Chemistry Group, Department of Natural Sciences, KVL

There is a group of researchers[18] who have been working together loosely for many years in order to define the properties and reactivity of nanoparticles in an environmental context – to develop and maintain safe water supply, to immobilize or treat waste, and to optimize dosages of pesticides and fertilizers. There have been projects over the past 20 years that have applied spectroscopies sensitive to the top 10 nm of solids; over the past 15 years, they have been using nanoscale microscopies, where the goal has been to define the mechanisms of uptake, release and degradation.

Here are case studies based on three natural nano-particulate minerals that are common in rocks, soils and sediments as well as water supply systems. These materials are stable and safe. They are calcite, $CaCO_3$, iron-oxides/hydroxides, and alumino-silicates. There are many other minerals with interesting potential, but these three demonstrate the range of problems that natural materials can and will be able to solve with help from nanotechnology.

The pollutants and beneficial components that interest us, that can move or not move in the environment, take many forms. Pollutants can be: i) inorganic, including heavy metals such as lead, arsenic, cadmium, nickel etc.; ii) organic, such as pesticides, halogenated hydrocarbons (solvents, dry cleaning fluids), spilled oil, drugs etc.; iii) radioactive, such as hospital and research waste and spent fuel rods stored by Denmark's neighbours; and iv) biological, such as viruses and bacteria that may be pathogens themselves or that produce unwanted compounds. Those that are beneficial include: inorganic and organic components necessary for plant and animal growth, and microorganisms that help degrade toxic materials to harmless ones or release beneficial compounds.

a) Nano materials in Water Treatment

Most municipal water supplies tap reservoirs in chalk or in glacial till, where chalk is a component. Some heavy metals, such as arsenic and nickel, are released to groundwater when pyrite in the chalk oxidizes. Chalk is often more than 90 percent calcite ($CaCO_3$) and this mineral's interesting open atomic arrangement allows easy uptake of toxic metals such as Ni^{2+}, Cd^{2+}, Pb^{2+} onto surfaces and into particles. Thus, groundwater at equilibrium with chalk has a built-in potential for self-treatment. A recent study (Roskilde County, Hedeselskabet and NanoGeoScience, Geological Institute, Copenhagen University) has shown that the very fine, bio-genic chalk particles remove nickel much more effectively than pure calcite with the same surface area. Bio-mineralization experiments with nanometer-scale elements of coccoliths, one of the components of chalk, are currently underway at NanoGeoScience, Copenhagen University, to define the parameters responsible for enhanced uptake, and to produce nanoparticles that improve on the natural material. This is an innovation with exciting possibilities. It takes a successful bulk technology and redefines it with nano scale materials.

When fresh groundwater is pumped from a well, it is aerated, usually by splashing over a series of concrete steps. H_2S (smells of rotten eggs) bubbles out and O_2 enters; dissolved Fe(II) oxidizes and nanoparticles of Fe-hydroxide (rust) precipitate. The flexibility of the iron oxide structure, its very high surface area, and its reactivity result in removal of

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18 Susan L. Svane Stipp, NanoGeoScience Group, Geological Institute, University of Copenhagen; Hans Christian Bruun Hansen and Christian Bender Koch, Environmental Chemistry Group, Department of Natural Sciences, KVL; Thomas H. Christensen, Erik Arvin and Hans-Jørgen Albrechtsen, Environment and Resources, DTU.

many heavy metals and organic components in a completely natural process, and one that is of great benefit to the water suppliers. However, costs can be reduced and safe drinking water production can be optimized by developing and stabilizing even smaller particles, and more important, altering their properties to optimize immobilization capacity. Research at DTU ER, KVL IGV and KU GI[19] is determining the controls of Fe-oxide nanoparticle production, the influence of biological intervention, and perspectives for surface modification. Projects are at the exploratory level; they aim at sophistication of the existing, bulk technology.

b) Nano Materials for Immobilization and Degradation of Waste

Waste repositories for non-degradable waste, such as heavy metals from fly ash or spent fuel from nuclear power generation, require special containment or treatment systems. Strategies include immobilization in a stable solid phase or impermeable liners and reactive barriers to slow or prevent transport in ground water. Natural nanoparticles are already playing a role; development will improve their properties.

Swelling clays such as bentonite have long been used as liners for waste canisters and for landfills where municipal waste and fly ash are dumped. The clay itself is reactive, and its ability to incorporate water in the mineral structure makes a tight seal to prevent further water movement. However, landfill liners have been improved by adding reactive components, for example by adding metallic iron, Fe(0). The crude but effective, patented 'Iron Wall Technology' uses ground scrap steel mixed with sand, filled in a trench dug with a bulldozer across the path of a ground water pollution plume. Dissolved, redox-sensitive pollutants are reduced as the iron rusts and the Fe(III)-oxide produces surface area for adsorption of other toxic components. An active component of the Iron Wall is green rust, a mineral of the layered double hydroxide (LDH) mineral family. In cooperation with several industries and research organizations, researchers from KVL IGV, DTU ER and GI KU NanoGeoScience are investigating ways to engineer LDH nanoparticles to improve effectiveness and increase security for immobilizing and degrading toxic compounds. Chlorinated hydrocarbons are converted to less harmful and more easily degradable compounds, nitrate is reduced, and carcinogenic dissolved chromium, Cr(VI), is reduced to immobile and non-toxic Cr(III). This research is at the exploratory level (nanoscience stage) but will lead to design of nano materials targeted for specific pollutants, engineered to dramatically improve efficiency over the crude, existing technology.

c) Dosing of Pesticides, Fertilizers, and eventually Drugs

Layered-double hydroxide (LDH) minerals are sandwich structures consisting of metal hydroxide layers alternating with interlayers. The interlayers are easy to manipulate so they can be designed to incorporate specific compounds and to release them under specific conditions. LDHs can be doped with surfactants, peptides or cyclodextrines in the interlayers or can be created to host medicine, hormones, pesticides, micronutrients, enzymes etc. for programmed release. Such dosage control protects the incorporated dopant from deactivation, decreases the quantity of bio-active ingredient needed, minimizes the risk of leakage to the surroundings, and reduces cost. LDHs with trapped enzymes can be coated on electrodes to produce sensors for which transformations are

19 Technical University, Environment and Resources; The Agricultural University, Environmental Chemistry Group, Department of Natural Sciences, NanoGeoScience Group; Geological Institute, University of Copenhagen.

catalyzed by the enzymes. The KVL group is focusing on design of LDHs through knowledge of their nano-scale properties. Some LDH materials are currently on the market but the manipulation of LDH to produce dosing products or sensors is at the exploratory stage.

Environmental assessment

a) Optimizing natural processes for removal of unwanted substances in drinking water is indeed an environmentally beneficial approach, especially if the natural removal properties can be enlarged without the additional use of energy or material resources. As with the modified starch polymers, there may be other technologies available with which the environmental impacts should be compared.

b) Problems of pollution of the ground water from deposits of toxic materials and compounds ranks high on the agenda since extracting clean water from the ground is felt by many to be an essential right; therefore, improvements in the technologies that ensure the supply of clean water are important. It must be considered to what degree the new nanotechnologies are environmental improvements of existing methodologies (or development trends in the existing methodologies); what the environmental impacts are throughout the life cycle of the technologies, e.g. the use of energy and material resources; how the materials are disposed of when used etc.

c) Excess use of chemicals due to overdosing of pesticides, medicine etc. is environmentally important. The developments of technologies such as LDH, which may facilitate more optimal use and less chemical spillage will probably be an environmental benefit. As for the other methodologies, it should be assessed whether the environmental impacts of using the new methodology during the life cycle balance out the impacts of the problem we are trying to solve.

Nano-particulate starch as a potential heavy metal and hydrophobic absorbent[20] - innovation for novel adsorption technologies

The pollution of water by heavy metals and toxic organic compounds pose a tremendous and growing global environmental problem. Among a multitude of technologies developed for removal of toxic matter in the environment, adsorption technologies based on biomass have considerable potential and have been extensively studied. Examples have included studies on absorption of metals, oil or other pollutants by chemically modified wood fibre, plant fibres or bark. Starch is one of the most significant renewable biopolymer resources on earth, with global annual production of pure starch amounting to some 40-50 million tonnes, and it is therefore an outstanding raw material for a number of applications (Ellis et al. 1998 *J.Sci.Food Sci*. 77, 289). Thanks to recent cross-disciplinary developments in biotechnology and polymer science (e.g. Blennow 2004, In: Starch in food: Structure, function and applications. A.-C. Eliasson, ed., p 97), the nanostructures of starch can now be specifically engineered to possess vastly different chemical and physical properties, many of which are industrially important.

One important challenge for the coming decade will be to explore the potential of starch for bulk applications in demanding and innovative hydrocolloid and solid systems. This will include the development of functionalized renewable bio-materials and more effective environmental absorbents (e.g. for flocculation of heavy metals: Crini 2005, *Progr.*

20 Data for this case has been provided by Senior Professor Andreas Bennow, The Royal Danish Agricultural University, and Senior Researcher David Plackett, Risoe national Laboratory.

Polym. Sci. 30, 38). Starch deserves particular attention in this respect as it provides interesting and attractive types of physico-chemical characteristics, chemical stability, high reactivity and selectivity towards a variety of compounds, resulting from the presence of chemical reactive and functional groups (hydroxyl, phosphate) and hydrophobic channels in the polymer matrix. Of specific interest is the recent proof of principle for the possibility of generating highly phosphorylated and thermally stabilized starch particles directly in the plant, based on work carried out at KVL (Blennow et al. 2005 *Int. J. Biol. Macromol.* accepted), enabling matrix nanostructures (e.g. well defined hydrophobic nano-sized channels) to be functionalized (e.g. with phosphate). These particles have been engineered to possess increased capacity for interactions with heavy metals and can potentially be improved for better selectivity as well as for selective hydrophobic interactions brought about by engineering the dimensions and the phosphate positioning within the nanochannels.

KVL is currently pursuing research on the mechanisms of absorption of copper ions to nano-engineered starch using EPR. At the Danish Polymer Centre (DPC) at Risoe National Laboratory, facilities for characterization of nano-structured starch are fully established, enabling disclosure of fundamentally new information concerning its absorption properties and other features using the wide range of state-of-the-art techniques available within the two organizations. Specific methods available include SEM, ESEM, TEM, AFM, CLSM (confocal laser scanning microscopy), XPS (X-ray photoelectron spectroscopy), FFF (Field Flow Fractionation), HR-MAS-NMR and ToF-SIMS (time-of-flight mass spectrometry).

From an industrial perspective, Denmark has strong and internationally competitive research activity in this field and Danish industrial groups (e.g. KMC and ISI, Cerestar-AKV) are firmly established with activities to pursue, develop and commercialize functionalized bulk biopolymers which may form the basis for the suggested eco-innovation.

Environmental assessment

The use of filters and adsorbents for removal/concentration of toxic materials in the environment is an important means of reducing potential environmental impacts. Several options have been used through the years (e.g. membranes and active carbon) and are well-established technologies. The possible environmental benefits of using nano-particulate starch must be evaluated through an assessment of the environmental impacts during the life cycle of the nanoparticulate starch compared to other filtration/adsorption techniques. Production in-vivo in green plants may be an environmental benefit. It must also be considered what additional benefits could be offered by using starch-based materials compared to active carbon or others e.g. in terms of more specific functionalization of the absorption.

The assessment must also consider that by using biomass and farm land such production withdraws materials from the pool of biomass. An important question is: What is the best way of using biomass?

Nano-porous materials for hydrogen fuel and diesel cleaning – eco-innovation in mobility[21]

21 Data for this case has been provided by Professor Claus Hviid Christensen, Center for Sustainable and Green Chemistry, Department of Chemistry, DTU.

Transport remains one of the major causes of air pollution from such substances as NO_x VOC, CO2 and particles, due to continuing and dramatic increases in the numbers of cars as well as the kilometres driven globally. EU environmental regulation has promoted innovations in environmental catalysts, which has decreased these emissions substantially; however, problems remain, particularly with diesel emission, notably in the form of particles. New stricter EURO IV emission standards for petrol- and now also diesel-driven cars necessitate further innovation in environmental catalysts. But innovation of new fuel systems are also under development within the automotive sector, although many technical problems still remain.

At the Technical University of Denmark (DTU), an interdisciplinary research team from NanoDTU has invented nano materials that improve the safe transport of hydrogen and ammonia. This innovation has implications for the development of fuel-cell driven cars as well as diesel cleaning. Technically, both of these opportunities rely on the use of self-generating nano-porous materials that allow unprecedented high storage capacities. Scientifically, progress relies on the research in catalysis and nano materials, where DTU is among the world leaders.

The technology aims particularly to solve the long-standing problem of reversible, high-density storage of hydrogen in a safe and environmentally acceptable form. This is one of the Grand Challenges in realizing a Hydrogen Economy, where hydrogen is used as a clean fuel for stationary and mobile units. The technology makes it possible already now to meet the 2015 targets set by the US Department of Energy in the technology road-map developed for mobile units. With the new technology, it will be possible, for example, to drive efficient fuel cell cars without (e.g.) any CO^2emissions.

As a spin-off from the main technology, it has also been possible to develop a new system that will allow safe transport of ammonia for use in selective catalytic reduction in diesel or lean-burn vehicles. With this new system, all maintenance and recharging can be performed at the regular service intervals of e.g. 25,000 km. Hereby, a breakthrough in diesel cleaning technologies is achieved.

Thus, the two new technologies may contribute in important ways to materialize a Hydrogen Economy and eliminate NOx-pollution from mobile and possibly also stationary units, which today represents a serious environmental problem.

Within the last year, the research breakthrough has resulted in three patent applications and as of April 2005, the commercial potential is being explored in the Danish start-up company AMMINEX A/S, which is a spin-off from DTU that will market and further develop the technologies.

Environmental assessment

Demand for transport is growing rapidly, and this has implications across many areas, including energy consumption, global warming and human health. Fuel-cell cars constitute one potential aim for reducing pollution and energy use. As mentioned, one challenge for the potential use of fuel cells is the storage of hydrogen, while another is the reduction in efficiency due to the conversion loss from hydrogen storage.

For the currently used technologies, catalytic cleaning of engine exhaust constitutes a major leap towards reduction of pollution with nitrogen oxides and VOC (both contributing to photochemical smog); for diesel engines, there is an additional reduction of emitted particles that constitute a major health hazard. Thus, improvements in this area will benefit the environmental performance of existing car engines.

As for the case study above, it is difficult to draw more specific conclusions concerning the overall environmental benefits of the technology, because the environmental assessment must include the total system of producing the engines and the hydrogen, through use and maintenance to the final disposal. This should be compared to currently used technologies (including their potential developments in energy efficiency, catalytic pollution reduction etc.).

5.4 Environmental assessment - system expansion or system substitution

An important aspect to consider in the evaluation of environmental benefits and risks is whether the developing technology will meet the needs of society in a new, more environmentally friendly way, or whether the technology creates new needs that may either reduce or increase pressure on the environment[22]. No definite answers can be given for an emerging technology, but some considerations can be presented, both in general and for more specific potential application areas. Here, the general aspects are dealt with based on the high-priority technology areas pointed out in the recently proposed Danish nano action plan (Ministry for Science, Technology and Innovation 2004). These are as already mentioned:

- Nanomedicine and drug delivery
- Biocompatible materials
- Nanosensors and nanofluidics
- Plastic electronics
- Nanooptics and nanophotonics
- Nanocatalysis, hydrogen technology etc.
- Nano materials with new functional properties

Nanomedicine and drug delivery is expected to be mostly a substitution. Current deliveries of drugs could be more efficient in terms of either being more specific in targeting the relevant receptors in the body or in releasing/dosing more correct amounts of medicine. Such developments could lead to a substitution of current drug delivery techniques, resulting in less use of medicine and possibly less releases to the environment. It may also lead to expansion of the areas within which the medicine is used and thus perhaps to a more widespread use of the medicine.

Bio-compatible materials will probably also substitute to a large extent currently used implants in humans. Another related aspect is nano-designed surfaces that inhibit or promote growth of microorganisms. Especially surfaces that inhibit growth may be used to substitute a wide array of biocidal applications.

Nanosensors and nanofluidics could be expected to cause an extension of the use of monitoring, since it may be possible to decentralize the analysis and maybe also to measure more. However, such an extension may be an environmental benefit, if it enables a faster reaction and problem solving up front.

22 The text in this section has been provided by Stig Olsen, IPU.

Plastic electronics is expected to cause a more dispersive and invasive use of electronics and will no doubt extend the use of electronics, possibly increasing its overall environmental impact.

Nanooptics and nanophotonics have different application fields, such as LED, polymer displays, and micro-structured fibres (for transmissions). The nanotechnology can substitute existing technologies for lighting and displays to a wide extent, but they may also result in extension of the use of e.g. displays.

Nanocatalysis, hydrogen technology etc. are expected to primarily substitute currently used technologies.

Nano materials with new functional properties cover a wide spectrum of materials and particles. Examples are magnetic nanoparticles used in data storage or nanoparticles absorbing specific wave lengths of light that are used in cosmetics. The area of application is so wide that it can be expected to both substitute existing technologies and to extend the use to new applications.

Given the enabling and in most cases emerging nature of nanotechnologies, they are likely to have profound effects on wide parts of the production and consumption patterns that need to be taken into consideration when assessing the overall environmental impacts of these technologies. We need to elaborate further on these issues.

6 Conclusion

The Danish nanotechnology development is still in a very early and formative stage of development. We are talking more about path creation in nanoscience than traceable technological trajectories. But it is also clear that right now these technological trajectories are in a critical stage of materializing. Many will emerge on a larger scale in the coming 5-15 years. The current phase of path creation seems therefore crucial for the direction nanotechnology is going to take.

Even though it can be contested to what extent nanotechnology is a new technology (or just a hype redefining existing practices), there are clear signs of novelty in the organization of knowledge production and in the modes of learning in the Danish nano community. New patterns of problem-solving activities are connected with the rise of the nano domain.

Eco-innovations are, however, to quite a large degree excluded from the attention rules, and they are weak in the search rules, although with some exceptions. Despite frequent references to the considerable eco-opportunities of nanotechnology in the general nano debate, both internationally and in Denmark, environmental issues are only a moderate part of the normal problem-solving activity in the Danish nano-technological community.

A very wide range of nano-related eco-potentials have been identified, not least the possibility of making the most detailed mapping of nano eco-potentials so far. This is due to the fact that there are some intrinsic features of nanotechnologies that may facilitate eco-innovation by making more tailored, efficient, selective and intelligent materials and products. Quite a few nanotechnologies thus possess eco-potentials, although they are not being developed with environmental benefits in mind.

In all, 39 suggested research areas/technologies are identified that offer eco-potentials within eleven different main nano research/technology areas.

They can contribute with environmental opportunities by aiming at:

1. *Smart tailored products* – for greater resource efficiency.
2. *New materials* **-** for less resource use and new properties.
3. *Energy production* – developing efficient or energy system alternatives to fossil fuels.
4. *Environmental remediation* **-** for more targeted handling of pollutants.

The 39 suggested research areas/technologies cover a very broad range of research and technology themes at very different development stages. Diversified assessments of opportunities and risks are therefore necessary.

It is generally too early to pick the environmental winners, given the very early stage of development, the immature materialization of nano manufacturing, and the many new research questions and technologies under way. Many (most) of the identified nano eco-potentials are at an experimental stage of development. Others are in early production (e.g. some functional surfaces techniques), and a few are fully commercialized (mainly catalysis and some sensors).

What we can say is that there are many very interesting eco-potentials related to different nanotechnologies, and that there are grounds to pursue and investigate the Danish eco-potentials of nanotechnologies further.

The interesting thing about the identified eco-potentials is that they in some cases may offer novel solutions to environmental problems. This may especially be expected from the fundamental nano research areas into new materials and functional surfaces from groups 1 and 2 above. This could lead to more radical and possibly widespread systemic eco-innovations, i.e. by creating materials and products that possess integrated "eco-properties" (e.g. anti-bacterial, self/easy-cleaning, insulating, strong and light, self-monitoring and self-diagnosing) for greater resource-efficiency, selectivity and durability. This could allow for more ongoing and decentralized smart eco-solutions and thereby a more preventive and integrated approach than practiced today.

But this is also where the environmental orientation among Danish researchers is most limited, and where it is least likely that the eco-potential will be exploited.

Also group 4, environmental remediation, may offer new approaches to environmental remediation by using nanoparticles to take more targeted action against specific pollutants, and by better exploiting the cleaning capacity of natural systems. The strong catalysis area is well-established and does not currently give rise to expectations of major novel solutions in the coming years, although there are exciting developments within diesel cleaning. However, novel environmental benefits may lie in the contributions this research makes to obtaining breakthroughs within hydrogen-based fuel systems. The mapping shows that nanotechnologies may also contribute in important ways to other new renewable and/or more efficient energy systems (group 3) and thereby to solving the central climate problems. Here, we find some of the more commercially promising but still emerging nanotechnologies, where Denmark holds quite a strong position, too. This may have an impact in the coming years.

We cannot conclude that nanotechnologies are green as such; it is, as yet, a much too diverse technological field for such a general statement. But overall, the identified eco-opportunities could make important contributions to novel solutions to environmental problems and overall for a more resource-efficient economy if materialized. This depends very much on how they are used and how they feed into other technologies.

The very strong Danish competencies within catalysis could provide a good basis for building a strong position within "green nanotechnology" here. But much indicates that this will not take place on its own. The emerging technological paths are only moderately green, and many of the identified eco-opportunities are being neglected. Even though environmental targets are not purposefully pursued in nano research, environmental advances may still be achieved through the general developments in nanotechnology. This is in fact presently the case with many eco-innovations (since eco-innovation has shifted somewhat from add-on technologies to less well-defined integrated technologies). But the environmental advantages are likely to be harvested later and to lesser extent, and some will not be pursued/selected at all. Naturally, it makes a difference if the research and development is aimed at, for example, the substitution of scarce or toxic materials improving the degradability and recycling abilities of materials and products, achieving dematerialization etc., particularly if the goal is to find solutions to specific environmental problems or to achieve major systemic change. The unexploited eco-potential is noteworthy considering the generally strong Danish competencies and policies on environmental issues. This is most surprising perhaps in the water area, where Danish industry holds strong competencies within water cleaning and supply, but where there is limited nano research and no linkages to the water industry.[23]

This illustrates the possible gaps between the high expectations and visions of nanotechnology and the actual processes taking place.

The suspicion of health and environmental risks from nanoparticles, and the measures lacking so far on how to handle these in risk and safety procedures, raises serious questions concerning the overall environmental benefits of the nanotechnologies based on these particles. This calls for at least a precautionary approach until more is known. Also, knowledge gaps exist concerning the wider environmental impacts of the other nano materials and various nanotechnologies. It is therefore important to investigate further into the eco-potentials and impacts of the *different* nanotechnologies and research areas listed and clarify the possibility to set up measures on how to handle the new risk challenges nanotechnology poses. In other words, we need to know both more about the opportunities and about the possible detrimental environmental impacts. The very early stage and therefore high uncertainty of some nanotechnologies means that it makes little sense to make environmental assessments of them; there is rather a need for more research and development into these areas, including their possible eco-potentials and -risks.

The many eco-potentials identified overall illustrate the very early and fluid stage of nanotechnology development globally and in Denmark. Much creativity is evident as streams of new research questions are raised. There is a multitude of future possible nano-technological paths. Which ones are going to materialize, and the part they may come to play on the market is currently highly uncertain – and depends also on policies. The high degree of uncertainty means that we need to acknowledge the fact that there are

23 Interview with Kasper Paasch, Danfoss Analytical, 7.9.2004.

limitations as to how much we can know now about both environmental opportunities and risks.

6.1 Challenges for policy

On the basis of the analysis made as well as input from the two innovation workshops and a policy workshop held during the foresight project, some key challenges are identified that policy should seek to address in seeking to facilitate a responsible and eco-efficient nanotechnology development.

A fundamental problem is the long "distance" in the innovation food chain from fundamental nano research to application areas and societal and environmental effects. An overall dilemma is when and how to carry out dialogues and policy measures in relation to a technological field such as nanotechnology, where technological materialization in the near- to medium- future is highly uncertain and very diverse. The early fluid stage of development means that there are currently good opportunities for influencing the direction of nanotechnology development, i.e. making it greener; at later stages, the lock-in into competencies and investments will be greater and transition costs therefore higher.

The more specific barriers are divided respectively into a risk and an opportunity section.

Barriers in the innovation system to handle nano risks are:

- Weak attention to environmental risks/detrimental effects related to nanotechnology among Danish nanoresearchers and industry.
- Existing risk assessment on environmental and health issues related to nanotechnology are lacking adequate procedures for standardised measuring, assessment and handling materials at the nano scale. There are specific problems to address which current regulation and procedures need to adapt to.
- Uncertainty – we have limited knowledge of the environmental and health effects related to nanotechnology, not least because of the very early stage of developments. We lack data and knowledge of how to gather and interpret data.
- There is increasing focus on toxicity, but there is also need to focus more broadly on "clean nanotechnologies" when assessing the environmental impacts, including investigating carefully the role of the widely different emerging nanotechnological subtechnologies.
- Hitherto lacking systematic incorporation of environmental assessments in research proposals (but proposed in EU as well as in the Danish nano action plan).
- Lacking nano competencies among risk/environmental assessments institutes and experts.
- Nanotechnology mediation is difficult due to the immense complexity, hype and uncertainty - there is a need for dialogues and serious scrutiny of nanotechnology in its diversity.

Barriers in the innovation system for nano eco-innovation are:

- Nano policies, e.g. EU's nano strategy and the Danish nano action plan, only focus on environmental risks and overlook barriers to eco-innovation.

- Weak attention to and belief in nano eco-innovation business opportunities except for the catalysis and energy area (need for regulation to create new markets, need for demonstrations…)
- Difficult to obtain environmental funding for fundamental nano research.
- Lacking environmental competencies in the Danish nano community and lacking nano competencies among environmental experts and policy makers.
- Weak linkages between the nano community (e.g. the new nano centres) and the environmental researchers/experts and the environmental industry.

Dedicated nanofunding for eco-innovation research and innovation programmes would be possible policy measures, but also demonstrations and testing of eco-opportunities, green visions and targets for nanotechnology development supported by fiscal measures, creating linkages and cooperation between nano experts and environmental experts could be important means for directing nanoresearch in a more green direction.

Eco-innovation in these basic sciences and enabling technologies is likely to have widespread effects on practically all kinds of technologies. Although it would be a new strategy for environmental policy to focus on these early stages of the innovation food chain, and thereby more long term development perspectives, it could be an efficient way to handle possible risks in due time as well as furthering systemic eco-innovations in the long run.

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Appendix 1 Interviews

Universities and research institutes

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Mission

To promote an innovative and environmentally sustainable technological development within the areas of energy, industrial technology and bioproduction through research, innovation and advisory services.

Vision

Risø's research **shall extend the boundaries** for the understanding of nature's processes and interactions right down to the molecular nanoscale.

The results obtained shall **set new trends** for the development of sustainable technologies within the fields of energy, industrial technology and biotechnology.

The efforts made **shall benefit** Danish society and lead to the development of new multi-billion industries.