Investigation of the impacts of selected nanotechnology products with view to their demand for raw materials and energy

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Abstract. In the study presented here qualitative and quantitative life-cycle considerations were employed to assess the potential material and energy savings that might be achieved through nano-enabled applications. Ten nanotechnology application fields with broad market coverage and immediate impact to either the generation of renewable energies or the use of critical resources were analyzed. Organic photovoltaic modules (solar cells that essentially consist of organic materials) and electronically dimmable windows (electrochromic laminated glass, which can be adjusted to conform to the ambient light conditions) as two very promising nano-enabled applications were quantitatively analyzed. Eight further products including neodymium magnets were evaluated on a qualitative basis. All assessments contain classical indicators such as energy efficiency, product carbon footprint, and resource consumption. In addition, pollutant aspects (exposure and toxicology) as well as other sustainability aspects (such as user benefits) were taken into account in the framework of a so-called “hot spot analysis”. Furthermore, drivers behind the innovation as well as associated rebound effects were identified. The results highlight the importance of product specific analyses based on a life-cycle thinking approach.

1. Introduction to the subject

Nanotechnology is already being used in a wide variety of applications. The conservation of resources and energy play a major role in the decision to employ nanotechnology. Important examples of this are the generation of renewable energies, thermal insulation, power storage, new (building) materials and industrial production processes.

On the one hand the expected savings potentials are based on the new opportunities for the exploitation of quantum effects in the semiconductor sector and on the other hand on the large specific surface area of nanostructured materials, which allows for increased material efficiency. Thanks to entirely new or improved mechanical, electrical, optical or magnetic properties, a reduction in the consumption of raw materials and energy can be achieved throughout the entire lifecycle of nanotechnological applications.
2. Objective of the study

In this context, the general objective of the presented study [1] is to describe the anticipated future resource and energy requirements of particularly promising nanotechnological applications and products both in qualitative terms and, as far as possible, in quantitative terms, with a view to analyzing the efficiency in the use of resources. To this end, it is essential to characterise the respective nanoactive components underlying an application and to identify the specific drivers for a nanotechnological functionalization or for the substitution of well-established materials. Finally, it will be investigated whether an increased use of nanotechnology in consumer products may result in rebound effects, which would counteract the goal of sustainability enhancement associated with these nanoproducts.

3. Methodological approach

For the survey, a total of ten practical examples of promising nanotechnology applications were analyzed in terms of the applications’ raw materials and energy demand. The study "Blueprint Germany" [2] which depicted the most important key technology fields with respect to combating the greenhouse effect and the need to raise energy efficiency in industrial production was used as a basis for the selection of the most promising fields of application. Uniform criteria were used in the selection of the application fields. Hence, the respective applications had to be suitable for the purpose of mass production and, in addition, already exist on the market or at least be on the verge of entering the market. In addition, the existence of a suitable, non-nanotechnology-based reference product was necessary to obtain a reference point for comparative analyses. Eight out of the ten examples were evaluated in qualitative terms, while two applications underwent a quantitative analysis.

The eight case studies that were evaluated from a qualitative point of view on the basis of the list of criteria¹ set out by the German NanoDialogue. The two quantitative case studies were evaluated via selected key indicators outlined in the Öko-Institut’s “Nano-Sustainability Check”². The key indicators “energy efficiency”, “product carbon footprint³” and “resource consumption” were chosen here. When considering the key indicator “resource consumption”, special attention was given to the evaluation of the metals and rare earths⁴ involved. In addition, toxicology as well as other sustainability aspects (such as user benefits) were taken into account in the framework of a so-called “hot spot analysis”.

¹ A tool elaborated by Issue Group 2 during the second phase of the NanoDialogue initiated by the Federal German Government (2009-2011), providing criteria for a qualitative analysis of the benefit and risk aspects of nanoproducts [3].
² Instrument developed by the Öko-Institut, which is primarily intended for enterprises, offering a systematic raster for an integrated approach relative to sustainability aspects of nano-enabled applications based on a quantitative analysis [4].
³ Quantitative parameter that expresses the greenhouse gas potential of a product; including the balance of all climate-relevant emissions along the entire life cycle of the product.
⁴ Rare earth metals comprise the chemical elements in the 3rd row of the periodic system (with the exception of actinium), as well as the lanthanides; they are needed for many high-tech products (e.g. electro-mobility, information technology, renewable energies) and often provoke conflicts due to their limited reserves and the complex production process.
4. Neodymium magnets

Neodymium magnets are an interesting nano-enabled application, allowing a qualitative investigation of the effects on resources and energy demand and the identification of possible rebound effects. The results are highlighted here as a typical example for the eight qualitative application studies.

Neodymium magnets are extremely powerful magnets, which are primarily made of nanoscale neodymium and iron powder [5]. They are of critical importance for industry, since they are a key component in many electrotechnical applications. They are indispensable, inter alia, for the conversion of electrical energy into kinetic energy (electric motor) and vice versa (generator). These magnets are most commonly used in modern wind turbines; in addition, neodymium magnets are integrated into loudspeakers, hard drives, and electric vehicles among other applications.

The use of nanoscale metal powders can increase the magnetic performance (the so-called energy product) by 10-30%. As a result, it is possible – in comparison to the reference product containing a conventional grain-size, metal powder - to save up to 30% of the required neodymium (Nd). [6]

In addition to neodymium, further rare earths such as praseodymium, dysprosium or terbium are needed for Nd magnets. Currently, approximately 70% of the worldwide Nd production is used for Nd magnets. The production of rare earths is characterized by complex technical measures, the release of toxic and radioactive substances (thorium, uranium, heavy metals, acids, etc.) as well as by particularly hazardous working conditions.

Due to the complex production process of rare earths and their limited reserves, it is of great economic and technological importance to further optimise the magnets to achieve either an enhancement of energy efficiency or a reduction of the weight of the rare earths used. The public acceptance and by extension the market share of electric mobility will have significant impact on the economic and technological development in this application sector. The electric motors in the automotive sectors could account for a significant portion of the neodymium used globally in the future.

Key drivers for switching to nano-scale Nd magnets are therefore the associated raw material savings in the field of rare earths and the enhancement of energy efficiency. Against the background that most of the world’s neodymium is mined in China, raw material savings of up to 30% are of particular relevance to industrial policy.

On the other hand, relevant rebound effects may arise from the production of Nd magnets, in particular taking into account the wide dispersal of the magnets used throughout the markets. With smaller and/or more efficient magnets it is possible to assemble small magnets into both cheaper products of equal efficiency, as well as into other, previously unattractive products. The development of new application areas is thus another key driver for nano-technological innovation. This might, however, result in direct rebound effects. Consumer demand for products with neodymium magnets might expand considerably, thereby boosting consumption of resources and favouring material dissipation. The savings potential that had been identified on the rare earths elements market could be negated; even the opposite of the desired effect might result from this development. In addition, the recycling of neodymium magnets – which is a complex matter anyway – is becoming less attractive because of the continuing size reduction of magnets and their broad-scale use.
5. Electronically dimmable windows

Electronically dimmable windows are made of electrochromic laminated glass, which dynamically, automatically or manually can be adjusted to conform to the ambient light conditions [7]. The electrochromic effect can be generated by using a thin film of nanostructured tungsten oxide, which - by applying a voltage - turns bluish as a result of a reaction with lithium ions. This glazing is suitable both for the private as well as for the commercial sector. The presented study, however, analyzed it in the context of its use in the commercial sector (such as in office buildings). On this market, it competes with mixed systems combining multiple glazing and shading devices which are often attached to the exterior of the building in the form of aluminum blinds (reference product).

The company EControl-Glas GmbH & Co. KG - which provided the necessary data for the application example - is the only supplier of electronically dimmable windows in Germany.

The detailed analysis of energy and resources aspects conducted by means of this data base comes to the conclusion that electronically switchable windows (nano-product) - as compared to the reference product - currently (scenario 2011) result in a significantly greater energy expenditure in production since the production facilities at EControl-Glas operate below their full capacity so far. It is not before the use phase that the new glazing becomes profitable in energetic terms. This is due to savings possible because of the lower energy consumption of air conditioning, lighting and the lack of necessity for external blinds that are also operated with the aid of electricity [8]. If the energy expenditure is converted into the CO$_2$ emissions resulting from the consumption, the following overall picture emerges:

|                        | Nano-product | Reference Product |
|------------------------|--------------|-------------------|
| PCF [kg CO$_2$/m$^2$] for the scenario 2011 | 256          | 304               |
| thereof Production     | 153          | 42                |
| Transportation         | 7            | 1                 |
| Use phase              | 96           | 262               |
| End-of-life stage      | 0            | -1                |
| PCF [kg CO$_2$/m$^2$] for the scenario 2020 | 201          | 304               |
| thereof Production     | 99           | 42                |
| Transportation         | 7            | 1                 |
| Use phase              | 95           | 262               |
| End-of-life stage      | 0            | -1                |

As can be seen from the above table, the results for the scenario 2020 show that the future situation is expected to change in favour of the nano-product. According to EControl-Glas, the energy efficiency in production will considerably improve with an increase in production volume by 2020.
Based on current information, a rebound effect emerges in the cold season only due to a slight increase in heating energy requirements as compared to the reference product. This adverse effect, however, does not nullify the savings from reduced cooling energy consumption, but slightly diminishes them.

With respect to resources, EControl glazing – in contrast to the reference product – requires the use of various metals that, in part, have been classified as critical in terms of their availability [9]. The above findings, however, should be seen in the light of the fact that the concentration levels of the relevant elements in EControl windows are typically very low. The annual production of EControl-Glas currently does not exceed 10 kg of tungsten, for example. This is about the tungsten amount needed for 65 sets of metal drills of a size between 1 and 10 mm, in which tungsten compounds are used as a curing agent. Even if the annual production of EControl-Glas would multiply itself per more than one hundred, this would not result in a significant rise in demand of any of the metals required.

Besides energy savings, an added value in terms of user benefits is also being achieved, which, however, is difficult to quantify: When a room is dimmed, the novel glazing selectively filters red and infrared light wavelengths out of the daylight spectrum. The resulting proportion of blue light in the room is demonstrably conductive to attention and concentration. Furthermore, the view from the windows will not be obstructed by blinds. Thus, this additional user benefits as well as the reduced energy consumption throughout the entire life cycle are the main drivers of this nano-innovation.

6. Organic photovoltaics

Organic photovoltaics (OPV) are solar cells that essentially consist of organic materials. As their plastic base materials are relatively easy to produce, OPV is considered to be an interesting alternative to conventional solar cells made up of inorganic semiconducting material (silicon) [10]. On the other hand, OPV modules - due to technological reasons - need fullerenes, i.e. nanomaterials, the production of which is particularly energy-intensive [11].

“Konarka PP 540”, the product evaluated here, consists of a coated polyethylene terephthalate (PET), during the production of which several layers are printed in a continuous process. It is characterized by a high degree of flexibility, allowing a three-dimensional deformation and adaptation to the installation site. The reference product chosen was a model consisting of thin film solar cells based on amorphous silicon (aSi). The evaluation of further current analyses [12] on the subject of energy efficiency leads to the conclusion that the primary energy requirement of OPV modules - despite the fullerenes required to produce them – is below the value of aSi modules by a factor of around 3, the main reasons being the small material input required for the OPV modules and the low-temperature processing.

Furthermore, OPV modules offer excellent overall performance even in poor lighting conditions and in case of an unfavourable incidence angle of the light. For that reason and thanks to their flexible properties they can allow for solar power generation at locations, where this would not be technically feasible with conventional solar modules. The greater degree of freedom as compared to conventional PV modules represents one of the major drivers for the development of OPV modules.
In addition, the relatively high silver content (0.5-5 %) of OPV modules makes them attractive for the recycling industry (in particular copper and precious metals smelters). This promotes the recycling of the metals and materials contained in the modules. Moreover, it can be expected that the fullerenes contained in the modules will be destroyed this way.

7. Conclusions

When considering the total of ten application examples investigated, it becomes apparent that, in general, nanotechnological innovations can save significant amounts of resources and energy. However, the potentials described above, depend at least partially on boundary conditions that still have to become a reality in the future. As regards electrically dimmable windows, for example, it is assumed that production capacities that are currently not being fully utilized could be operated more efficiently in the future thanks to serial production on a large scale. Otherwise, the energy savings potentials of about 30 % as compared to conventional windows could not materialise.

Thanks above all to the qualitative analysis of several application fields, it was possible to determine the impact of new developments in nanotechnology on the consumption rate of critical metallic raw materials and the potential rebound effects that might occur. A good example of this are sintered neodymium magnets, where potential rebound effects that might occur as a result of increasing demand and broad-scale use are hindering the objective initially pursued, that is to reduce the specific consumption of rare earth resources.

With regard to the driving forces behind the investigated nano-enabled applications, it is found that, in addition to traditional drivers such as cost savings and the opening-up of novel application fields, issues such as material saving and energy efficiency in particular have recently become major drivers for innovation. This can be illustrated by the example of the Nd magnets, but is also obvious in the fields of energy technologies, industrial production processes, as well as (building) materials.

Against the background of this study, it again becomes particularly obvious that - with regard to the effects of nanotechnological products on the consumption rate of raw materials and energy, as well as for the determination of relevant rebound effects - the analysis of the entire life cycle of the application under consideration is an absolute prerequisite for obtaining reliable results.

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