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NANOTECHNOLOGY FOR GREEN INNOVATION

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FOREWORD

The paper brings together information collected through discussions and projects undertaken by the OECD Working Party on Nanotechnology (WPN) relevant to the development and use of nanotechnology for green innovation. It relies in particular on preliminary results from the WPN project on the *Responsible Development of Nanotechnology* and on conclusions from a symposium, organised by the OECD WPN together with the United States National Nanotechnology Initiative, which took place in March 2012 in Washington DC, United States, on *Assessing the Economic Impact of Nanotechnology*. It also draws on material from the four background papers that were developed for the symposium. The background papers were:

- “Challenges for Governments in Evaluating the Return on Investment from Nanotechnology and its Broader Economic Impact” by Eleanor O’Rourke and Mark Morrison of the Institute of Nanotechnology, United Kingdom;
- “Finance and Investor Models in Nanotechnology” by Tom Crawley, Pekka Koponen, Lauri Tolvas and Terhi Marttila of Spinverse, Finland;
- “The Economic Contributions of Nanotechnology to Green and Sustainable Growth” by Philip Shapira and Jan Youtie, Georgia Institute of Technology, Atlanta, United States; and
- “Models, Tool and Metrics Available to Assess the Economic Impact of Nanotechnology” by Katherine Bojczuk and Ben Walsh of Oakdene Hollins, United Kingdom.

The purpose of the paper is to provide background information for future work by the WPN on the application of nanotechnology to green innovation.

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EXECUTIVE SUMMARY

The need for development of affordable and safe ways of addressing global challenges, in areas such as energy, environment and health, has never been more pressing. The global demand for energy is expected to increase by more than 30% between 2010 and 2035 (International Energy Agency, 2011). More than 800 million people worldwide are currently without access to safe drinking water (WHO, 2010). Such challenges have resulted in increasing attention being paid by policymakers, researchers, and corporations to new technologies, and the application of technologies in new ways. Green innovation is one such new way of addressing global challenges.

Green innovation is innovation which reduces environmental impacts: by increasing energy efficiency, by reducing waste or greenhouse gas emissions and/or by minimising the consumption of non-renewable raw materials, for example. OECD countries and emerging economies alike are seeking new ways to use green innovation for increased competitiveness through a transition to a so-called “green growth” scenario based on the application of technology (OECD, 2012a). Within the group of technologies which are expected to help to contribute to that transition, nanotechnology is attracting particular attention.

Since it began its work in 2007, the OECD Working Party on Nanotechnology (WPN) has developed a number of projects addressing emerging policy issues of science, technology and innovation related to the responsible development of nanotechnology. During that time, discussions within the WPN have increasingly highlighted the potential of nanotechnology to support green growth, focusing on two particular aspects: *i)* the potential for nanotechnology to contribute to green innovation; and *ii)* the potential and perceived risks and environmental costs of using the technology. The second of these may reduce the ability of nanotechnology to achieve its green goals, i.e. to meet its “green vocation”.

Green nanotechnology in the context of a green innovation transition

Nanotechnology for green innovation – green nanotechnology – aims for products and processes that are safe, energy efficient, reduce waste and lessen greenhouse gas emissions. Such products and processes are based on renewable materials and/or have a low net impact on the environment. Green nanotechnology is also about manufacturing processes that are economically and environmentally sustainable.

Green nanotechnology is increasingly being referred to in connection with other concepts such as green chemistry and sustainable and green engineering and manufacturing. The principles of green chemistry can be applied to produce safer and more sustainable nanomaterials and more efficient and sustainable nano manufacturing processes. Conversely, the principles of nanoscience can be used to foster green chemistry by using nanotechnology to make manufacturing more environmentally friendly.

Green nanotechnology can have multiple roles and impacts across the whole value chain of a product and can be of an enabling nature, being used as a tool to further support technology or product development, for example:

- Nanotechnology can play a fundamental role in bringing a key functionality to a product (e.g. nanotechnology-enabled batteries);

- Nanotechnology may constitute a small percentage of a final product whose key functions hinge on exploiting the size-dependent phenomena of nanotechnology (e.g. electric cars using nanotechnology-enabled batteries);
- Nanotechnology can improve or enable sustainable and green processes that lead to the development and production of a nanotechnology-enabled product without that final product containing any nanomaterials.

Significant advances have been made in the field of nanotechnology in the past decade and more, helping it to move closer to achieving its green potential. However, the economic and environmental sustainability of green solutions involving nanotechnology is in many cases as yet unclear and some novel solutions bring with them environmental, health and safety (EHS) risks (e.g. high energy manufacturing processes and processes which may rely on toxic materials). These risks must be mitigated in advancing green nanotechnology solutions.

Green nanotechnology is expected to increasingly impact on a large range of economic sectors, ranging from food packaging to automotives, from the tyre industry to electronics. Nanotechnology is also increasingly being applied in conjunction with other technologies, such as biotechnology and energy technologies, leading to products incorporating multiple green technological innovations.

The policy environment for green nanotechnology

When reviewing government strategies for science, technology and innovation, the presence of nanotechnology for green innovation is apparent. Recurrent priorities in governmental programmes include nanotechnology for energy production and storage; nanotechnology for water treatment; and nanotechnology for the environment (in particular, in reducing pressure on raw materials and in fostering sustainable manufacturing and sustainably manufactured products).

In many countries, supports for green nanotechnology have been mainstreamed within more general efforts to 'green' the trajectory of the economy. Green nanotechnology operates in a complex landscape of fiscal and legislative policies and allied measures for green growth and science, technology and innovation. Framing conditions - such as regulation, standards and research, environmental and enterprise policy – are strongly influencing the development of green nanotechnology for processes or products.

If the reasons behind investment in nanotechnology vary to some extent at national levels (depending on national scientific and economic specialisations, competitiveness goals and societal objectives), there still remains a common trend, visible in both OECD and emerging economies, in governments seeing nanotechnology as having the potential to address social and environmental challenges while supporting industrial competitiveness and economic growth. Policies for green nanotechnology broadly aim to facilitate its development and its potential to be used for efficient, affordable and safe applications. Technology policies mainly take the form of R&D investments – increasingly directed towards more applied research although basic research is often retained as an important area for investment – and support for small and medium size enterprises (SMEs). Efforts are also being made to reduce uncertainty around the use of nanotechnology (especially regulatory uncertainty) and to ensure responsible development. These are evidenced in the investment in a growing number of initiatives (at national and international levels) which are looking at environmental health and safety (EHS) risks and ethical and social issues.

Diminishing and sharing the costs of the development and commercialisation of green nanotechnology (i.e. risk reduction and sharing) is also a focus for policy intervention. Although green nanotechnology is increasingly demonstrating its potential to move out of the laboratory and into concrete solutions for products and processes, there is still a great hesitancy from companies to lead the way. This reluctance derives from a number of factors including the risks associated with the technology (e.g.

consumer acceptance, EHS, ethical and social risks); regulatory uncertainty; the lack of maturity of the technology; market uncertainty; the low number of successful demonstrators of the benefits of using nanotechnology (in the form of green nanotechnology products already on the market); and a strong competition with traditional technologies and production techniques.

For nanotechnology to address major environmental and societal challenges, products using nanotechnology need to be manufactured and used in large volumes. Funding is needed to support prototyping and pilot manufacturing, as this is a point at which costs and risk are at their highest, discouraging corporations and institutional investors from funding these activities. Policies are increasingly being developed which are directed at funding proof of concept, pilot and demonstration projects.

In addition, efforts are being made to strengthen the links between public and private entities. Industrial consortia are being developed with the support of, and sometimes initiated by, public bodies, for example, the NanoBusiness Alliance in the United States and the Nanotechnology Industries Association in Europe. At the research, development and early commercialisation stages, more innovative approaches to sharing risk and knowledge are also being developed based on large consortia comprising companies, public laboratories and institutions (e.g. Genesis, InnoCNT, NanoNextNL). Such consortia allow for risk sharing between public and private entities, but also risk sharing among companies themselves. Consortia may also help to manage the uncertainty of bringing a product to market when no similar technologies have previously been commercialised or when the demand for the technology/application is not yet clear.

There is also a general trend to reinforce the links between public entities themselves. Within the OECD and emerging economies, co-ordination between different ministries, agencies and departments to support nanotechnology and nanotechnology for green applications was commonly seen in WPN projects.

There may also be a role for demand-side policies supporting the development and commercialisation of nanotechnology for global challenges, including the use of green nanotechnology. Scenarios are often seen in nanotechnology product development in which producers are reluctant to invest in options for which customers and users are not yet articulating a clear demand or where no clear products options are identified as yet. This uncertainty about market perspectives and customer/user demand and requirements is being addressed through new alliances and consortia, as mentioned above, but there may also be a need for interventions to further reduce the uncertainty, including demand-side policies.

The potential impact of nanotechnology on green innovation

Increasingly, as the technology is being developed, efforts are being made to try to find ways of assessing or tracking the impact of nanotechnology on specific policy objectives such as green growth. This is a very challenging task due to the sheer number of applications of nanotechnology across all economic sectors and its broad enabling nature, as well as the potential for it to impact across value chains and to create a complex setting for any robust impact analysis. The potential risks of new green nanotechnologies might need to be compared with those of current technologies (which may, for example, also be energy intensive and present various risks) and against the human and environmental costs of not effectively addressing key global challenges (such as reducing carbon emissions or providing potable water). The policy landscape in which nanotechnology operates is complex, evolving and responsive to economic and social challenges. A wide range of potential economic, environmental and societal implications of the technology needs to be included in methodologies for assessing the impact of green innovation through nanotechnology.

CHAPTER 1: INTRODUCTION TO GREEN NANOTECHNOLOGY

Since it began its work in 2007, the OECD Working Party on Nanotechnology (WPN) has developed a number of projects addressing emerging policy issues of science, technology and innovation related to the responsible development of nanotechnology. During that time, discussions within the WPN have increasingly highlighted the potential of nanotechnology to act as a support to green growth. This growing interest at the WPN concerns two aspects: the potential of nanotechnology to contribute to green innovation and the potential and perceived risks and environmental costs involved in using nanotechnology. This project draws on those discussions and on the outcomes and background papers of the joint OECD/National Nanotechnology Initiative Symposium on *Assessing the Economic Impact of Nanotechnology* (March 2012), as well as on WPN projects on the responsible development of nanotechnology and on the use of nanotechnology for green growth.

This chapter considers the definition and application of green nanotechnology. Chapter 2 addresses the strategies being implemented to support green nanotechnology. Chapter 3 examines the impact and potential impact of nanotechnologies for green innovation and some of the challenges in assessing those impacts.

What is green innovation through nanotechnology?

As green innovation is not yet clearly defined (Schiederig et al., 2011), there can be no clear definition of what nanotechnology for green innovation – green nanotechnology – should encompass. From published papers on the issue, one could describe green nanotechnology as a foundation for products and processes that are safe and have a low net environmental impact, being energy efficient, reducing waste, lessening greenhouse gas emissions and using renewable materials. Green nanotechnology can be seen as supporting the development of sustainable solutions to address global issues such as energy shortages and scarcity of clean water, and many other areas of environmental concern, and being present in environmentally-sustainable manufacturing processes.

Green nanotechnology is linked to other concepts such as green chemistry and sustainable and green engineering and manufacturing (ACS Green Chemistry Institute/Oregon Nanoscience and Microtechnologies Institute, 2011; Project on Emerging Nanotechnologies, 2007) (see Box 1).

Box 1. Green chemistry/Green manufacturing/Green nanotechnology

Green chemistry is an approach to chemical synthesis that considers life cycle factors such as waste, safety, energy use and toxicity in the earliest stages of molecular design and production, in order to mitigate environmental impacts and enhance the safety and efficiency associated with chemical production, use and disposal. It takes a life-cycle approach to minimising undesirable impacts that can be associated with chemicals and their production.

The Sustainable Manufacturing Initiative of the US Department of Commerce describes sustainable manufacturing as: "The creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities and consumers and are economically sound."

The principles of green chemistry can be applied to produce safer and more sustainable nanomaterials and more efficient and sustainable nano-manufacturing processes. Green chemistry principles are, for example, used to manufacture nanomaterials from less toxic chemicals, using less energy and less of certain scarce raw resources. Conversely, the principles of nanoscience can be used to foster green chemistry by using nanotechnology to make manufacturing processes for non-nano materials and products more environmentally friendly.

In general, green nanotechnology is closely interconnected with both principles of green chemistry and green manufacturing.

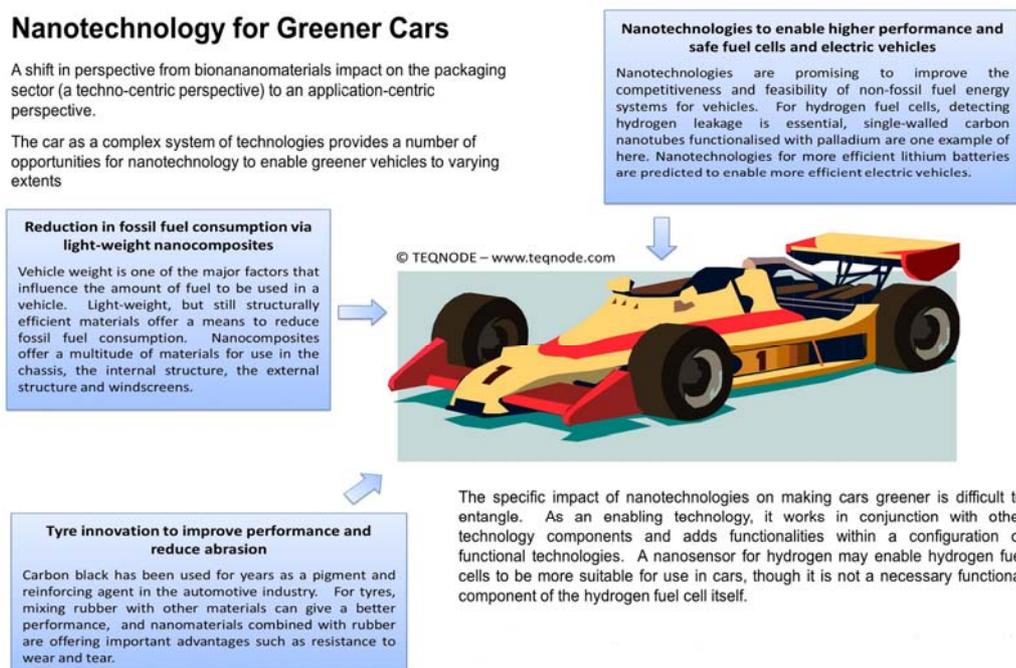
Note: For more information see: <http://trade.gov/competitiveness/sustainablemanufacturing/index.asp>

Green nanotechnology can have multiple roles and impacts across the whole value chain of a product and can be of an enabling nature, being used as a tool to further support technology or product development, for example:

- Nanotechnology can play a fundamental role and bring key functionality to a product (e.g. nanotechnology-enabled batteries);
- Nanotechnology may constitute a small percentage of a final product but the key “green” functions of this product hinge on exploiting size-dependent phenomena underlying nanotechnology (e.g. electric cars using nanotechnology-enabled batteries)
- Nanotechnology can improve or enable more sustainable and green development and manufacturing processes without the final product containing any nanomaterials.

Green cars, for example, are complex products which incorporate green nanotechnology in several different ways, being present in the tyres, in the chassis, in the windscreen, etc. (see Figure 1). Nanotechnology also enables components of the green car, and its production, for example, through the use of sensors to reduce energy wastage and to monitor and reduce emissions.

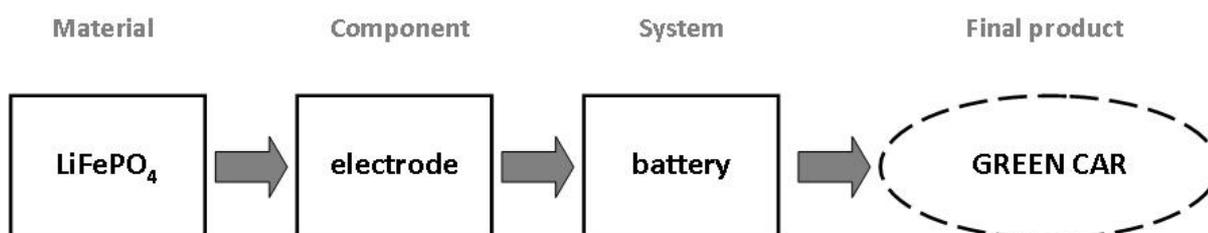
Figure 1. Example of nanotechnology for greener cars



Source: Adapted from Robinson DKR (2013), "Indications of socio-economic impacts of nanotechnologies", forthcoming chapter in the edited volume of the fourth annual conference of the Society for the study of Nanoscience and Emerging Technologies (S-NET). www.utwente.nl/igs/conference/2012_snet_conference/

Examination of the power storage and release system within green cars (see Figure 2) illustrates the value of green nanotechnology but also the difficulty in quantifying that value. The battery material (LiFePO_4), the component electrode and the system as a whole (the battery) are all based on nanotechnology, so the final product (green car) is nano-enabled through its batteries i.e. its performance is enhanced by the use of nanotechnology. However, nanotechnology represents just a small percentage of the final product.

Figure 2. Value chain – nanotech-battery in a ‘green’ car



Source: OECD/NNI Symposium on Assessing the Economic Impact of Nanotechnology, Background paper: Challenges for Governments in Evaluating Return on Investment from Nanotechnology and its Broader Economic Impact, Eleanor O'Rourke and Mark Morrison, Institute of Nanotechnology, United Kingdom, see: nano.gov/symposium.

Nanotechnology is increasingly being used for green applications in conjunction with other technologies and disciplines such as biology and life sciences, materials and environmental sciences and electronics and computing, leading to products that encompass multiple technological innovations.

Applications of nanotechnology for green innovation: some examples from WPN case studies

Green nanotechnology is expected to impact on a large range of economic sectors, ranging from food packaging to health, from the tyre industry to electronics. The WPN has been looking at green applications of nanotechnology, with an ongoing case study on nanotechnology for environmentally sustainable tyres, and case studies under development¹ on *i*) the development of micro- and nanofibrillar cellulose; *ii*) nanotechnology for efficiency of electronic and optical components; and *iii*) carbon nanotubes for green innovation. Summaries of the background and progress to date on these case studies are given below.

Nanotechnology for the sustainable development of tyres

Millions of people and industries rely today on road transport and the number of road vehicles is expected to double by 2030. Servicing this new demand will present a significant challenge in the area of tyres as current production relies greatly on natural rubber and petrochemicals. Modern tyres already incorporate nanotechnology and achieve their high mileage, durability and road grip through the use of nanoscale carbon black and silica. Although incremental improvements to current tyre technology can be expected, the industry is reaching the technical limits of tread compound development. New nanotechnology applications could provide scope for dramatic improvements on existing technologies.

The introduction of carbon black and silica has already allowed manufacturers to achieve performances that would not have been possible using conventional materials. Carbon black has been used for decades (in various size ranges) and recent scientific breakthroughs now allow both carbon black and silica to be economically produced at the nanoscale and incorporated into tyres (and other) consumer products. Many predict that other nanomaterials will be introduced into manufacturing processes to increase performance, providing added environmental and socio-economic benefits. Potential fields of

improvement include increased car and truck fuel efficiency and tyre durability and reduced greenhouse gas emissions and tyre weight. Whilst there are still concerns about the degree to which nanomaterials can leach into food from the packaging, and the effect they may have on the health of consumers, most research so far looks promising, and the benefits are highly tangible - several nano-enhancements for packaging are already on the market, helping to prolong the shelf life of food and making it easier to manufacture, process, and manage. Whilst there are still concerns about the degree to which nanomaterials can leak into food from the packaging, and the effect they may have on the health of consumers, most research so far looks promising, and the benefits are highly tangible - several nano-enhancements for packaging are already on the market, helping to prolong the shelf life of food and making it easier to manufacture, process, and manage. Whilst there are still concerns about the degree to which nanomaterials can leach into food from the packaging, and the effect they may have on the health of consumers, most research so far looks promising, and the benefits are highly tangible - several nano-enhancements for packaging are already on the market, helping to prolong the shelf life of food and making it easier to manufacture, process, and manage.

Some of the most promising nanomaterials for tyres include nanosilica, organoclay and carbon nanotubes (CNTs) used as fillers, substituting for traditional fillers like carbon black and silica. Composites reinforced with CNTs have been shown to have dramatically improved tensile strength, tear strength and hardness compared with more conventional materials (Xiangwen, 2010). Silicon carbide has been used to produce tyres with improved skid resistance and reduced abrasion (of nearly 50% according to patent data²). Nanoparticles of clay can be mixed with plastic and synthetic rubber to seal the inside of tyres, creating an airtight surface and allowing the amount of rubber required to be reduced (see Box 2).

Box 2. OECD Project on Nanotechnology for Sustainable Development of Tyres

The OECD Working Party on Nanotechnology, together with the OECD Working Party on Manufactured Nanomaterials, is developing a case study on Nanotechnology for the Sustainable Development of Tyres. Tyres are well-known, easily identifiable mass products that will continue to be required well into the future. The tyre industry faces many challenges - from the on-going supply of raw materials in the face of massive predicted growth in demand for vehicles over the coming decades, to implementing innovations that will improve the sustainability of cars, e.g. through the reduction of CO₂ emissions, while still delivering a high-quality product with a critical role in vehicle safety. Tyres thus represent a good case study through which to analyse and identify safety, technical, socio-economic and policy issues relating to the use of green nanotechnology.

The case study is examining the following issues:

- **The Status of the Technology:** review of the current status of technology in the tyre industry, focusing on the use of nanomaterials and nanotechnology and enabling technologies. This could also include examination of the changing nature of innovation in the industry as well as anticipated technologies for the future.
- **Societal Impacts:** assessment of the socio-economic impacts that may be realised as a result of the use of new nanomaterials in the tyre industry.
- **Positive and Negative Environmental Impacts in the Context of LCA:** evaluation of the potential positive and negative environmental impacts from different types of tyre technologies including existing ones and those currently at the R&D stage:
- **Environmental Health and Safety Risks and Best Practices:** detailed consideration of the environmental health and safety procedures for the development and use of nanomaterials in the tyre industry.
- **Knowledge and Best Practice Transfer:** Examination of the transfer of knowledge and best practice on environmental health and safety (EHS)

The tyres case study started in 2012 and will be completed in late 2013.

Micro- and nanofibrillar cellulose

Cellulose fibres constitute an abundant, renewable and biodegradable raw material which can be used in paper production and other applications. Fibres have been used for the production of paper for almost 2000 years, with wood, which is abundant in many countries globally, having been used as a raw material in the form of fibres for approximately 150 years. The use of nanofibres from wood pulp may open up new opportunities for forest based industries.

Globalisation and increased international competition within the pulp and paper industry demands new thinking: increased refinement ratios, new technology and new production methods. Next step innovation requires the production and refinement of micro- and nanosized materials from cellulose - micro- and nanofibrillar cellulose (MFC and NFC). While there has been great interest in such fibres for a long period of time, given the variety of potential applications in the form of paper and packaging materials, manufacturing has been a significant obstacle to commercial exploitation. The manufacturing process has been considered too energy-intensive and complex to apply but advances in research are now making headway in addressing these issues for fibrous nanomaterials.

Nanotechnology for efficiency of electronic and optical components

Until recently, electronic devices were not considered as major consumers of energy compared with engines or heating systems. However, as more devices are being used, energy consumption by these devices has become a larger issue. The dramatic increase in performance of electronic components, resulting from improvements in both manufacturing efficiency and semiconductor design (MOS transistors, LED and laser diodes), has resulted in greater usage among the general population, leading to increases in energy consumption. This can be observed in the energy consumption of super-computers used for high-performance or cloud computing (for example Google's server farm requires up to 260 MWatts, which is equivalent to the consumption of 200 000 households),³ as well as in the countless number of devices (smartphones, TVs, sensors, etc.) used by the general population, each of which uses very little energy but which, as a whole, have a significant impact on global energy consumption. Likewise, a modern television uses more energy than older cathode ray tubes because their screens are wider and brighter and have better resolution and contrast.

The demand for energy efficiency in mobile devices first started because of the limited capacity of batteries. The desire for greater mobility was the main driver of the success of small and less powerful processors used in smartphones or notepads, to the detriment of major manufacturers such as AMD or Intel. Efforts to optimise energy consumption have even resulted in software engineers trying to code programmes to reduce energy use, even at the cost of reducing processing speed.

Nanotechnology has made lower energy consumption per-bit possible (or per emitted photon in optical devices) with a concurrent increase in the performance of the whole electronic component more than compensating for any diminution of other properties. Today the energy performance of an electronic chip is limited mostly by the power lost through thermal dissipation (typically 200 W/cm²).

However, the reduction in the energy and raw materials usage per device has not been sufficient to offset the global energy consumption caused by new functionalities and performance which increasingly require greater use of energy. New “zero-power” systems are being developed in which low-energy electronics use energy harvesters to convert ambient energy into electrical energy (photovoltaics, piezoelectrics, thermic, etc.). Nanotechnologies are at the forefront of the race for low energy consumption through modifications in the technologies used in electronics. Novel devices are being developed based on spintronics, on electromechanical nanosystems (NEMS) and using optical rather than metallic

interconnections. LED-based new technologies have the potential to revolutionise lighting, which to date has mainly been based on gas discharge lamps using an electric arc in vaporised mercury.

Carbon nanotubes for green innovation⁴

There are many potential applications for carbon nanotubes, the most relevant to green innovation being for applications relating to transport and electronics.

Transport

Modern life would be inconceivable without mobility, but traffic and transport systems must be consistently adapted to the changing requirements of humans and markets. Increasingly, the focus of modern mobility is on requirements for environmentally-compatible approaches with a high level of safety.

Materials technology plays a vital role in the development of energy-efficient concepts. High-strength, low density synthetic materials and composites can be used to lower the weight of components, with that reduction translating into energy savings. CNT-based materials have great potential to improve the energy use of the transport sector including cars, lorries and trains. CNT-reinforced plastics and metals are especially lightweight, while offering high levels of stability and strength. These properties are also ideally suited to meet the extreme material requirements of the aviation and space industry.

Conventional design materials currently used in aeronautical applications, the automotive industry and machinery are increasingly reaching the limits of passive structures. Lightweight construction concepts based on CNT offer enormous potential, including their use in situations with extraordinary structural stresses. High-strength, ultra-light materials being used for lower-weight designs of cars and aircrafts are making an important contribution to higher energy and resource efficiency and substantial amounts of fuel saving.

Lightweight construction also offers potential benefits to other applications and industries. CNT-based particle foams offer improved vehicle security, while specialised forms of concrete offer additional design options and improved earthquake protection.

Electronics

The success of nearly all sectors of industry today is closely associated with their electronic systems, without which many applications would not be feasible. At the same time, the complexity of these systems has increased tremendously over recent years. Innovative solutions that contribute to the control of demanding electronic applications and simultaneously conserve natural resources are of great significance for the entire economy.

The development of increasingly-powerful electronic components, together with more cost-effective and application-specific production, will benefit from the opportunities offered by nanotechnology. Innovation based on CNTs with both outstanding electrical conductivity and mechanical properties are particularly promising. They range from displays to X-ray and microwave generators to photovoltaic applications and high-resolution electron beam instruments.

In all of the above case studies it is also important to cover the potential health, environmental and safety (EHS) aspects. These will be introduced in further detail in the next section.

Green innovation through nanotechnology: Responsible development

Green nanotechnology brings significant potential gains at environmental, societal and economic levels, but there are also potential risks and costs. Advances have been made in the application of green nanotechnology: however, there are still concerns about the level of sustainability of certain green applications of nanotechnology and actual or perceived environmental, health and safety (EHS) risks (Royal Commission on Environmental Pollution, 2008).

While green nanotechnology applications may save energy and reduce carbon emissions in the final product, there are concerns about the amount of energy that might be involved in the upstream production of component nanomaterials.⁵ With on-going research in the field, energy and manufacturing costs for nanomaterial production are likely to reduce over time as process technologies are improved and new materials emerge. Nonetheless, the energy, waste and resource extraction costs associated with the production of the materials used in green nanotechnology applications remain an important part of the equation in assuring the responsible development of green nanotechnology. As the overall field of nanotechnology raises concern about potential EHS risks, as well as ethical and social issues, this is no different for the green nanotechnology area. Concerns are, for example, linked to potential EHS risks through the use and disposal of nanostructures employed in green nanotechnology applications.⁶

Many recent and current nanotechnology EHS studies contain calls for further research and monitoring, e.g. for research into more biocompatible alternatives. Many national and international initiatives are also being developed in order to better understand those risks and to reduce uncertainties in the field, as discussed in Chapter 2.

CHAPTER 2: STRATEGIES FOR GREEN INNOVATION THROUGH NANOTECHNOLOGY

In many countries, supports for green nanotechnology have been mainstreamed within more general efforts to 'green' the trajectory of the economy. Green nanotechnology operates in a complex landscape of fiscal and legislative policies and allied measures for green growth and for science, technology and innovation more generally. Framing conditions - such as regulation and standards, and research, environmental and enterprise policy – strongly influence the development of green nanotechnology for use in processes or products.

Policy to support green nanotechnology includes significant R&D efforts that are increasingly applications orientated and driven by grand challenges. Policy interventions to share and diminish the risks inherent in the development and commercialisation of applications involving green nanotechnology are resulting in the creation of innovative public-private collaborations. Efforts to ensure that nanotechnology is developed in a responsible manner are being supported through investment and there is a growing number of initiatives (at the national and international level) looking at environmental health and safety (EHS) and ethical and social issues. There are also initiatives aiming to ensure the environmental and economic sustainability of manufacturing processes involving nanotechnology.

Overview of national strategies

The perception by many governments that nanotechnology offers significant potential for green innovation is apparent in their strategies for science, technology and innovation. Recurrent priorities in governmental programmes include nanotechnology for energy production and storage; nanotechnology for water treatment; and nanotechnology for the environment (in particular, in reducing pressure on raw materials and in fostering sustainable manufacturing and sustainably manufactured products).⁷

If the reasons behind the investment in nanotechnology vary to some extent at national levels (depending on the national characteristics of their scientific and economic systems, their competitiveness goals and their societal objectives), there remains a common trend, visible in both OECD and emerging economies, in governments seeing nanotechnology as having the potential to address social and environmental challenges while supporting industrial competitiveness and economic growth. When looking at different government strategies for science, technology and innovation, there is a clear interest in the possibilities that nanotechnology offers in supporting green innovation and green growth. Nanotechnology appears as an important component of technological options for transitioning to green innovation (see Box 3).

Box 3. Examples of national priorities in relation to green innovation through nanotechnology

Brazil: The Inter-Ministries Nanotechnology Committee, created in 2012, has defined a number of strategic areas for the development of nanotechnology in the country. Two of the six areas identified are energy and the environment. In particular, in the environment area, the main goal is developing new materials from biomass (e.g. plastic, rubber, nanocomposites). In the energy sector, the priority is to increase the efficiency and quality of products and processes and to increase the integration of features (e.g. sensors, electronics devices).

Germany: Nanotechnology is addressed through the “Action Plan Nanotechnology 2015”. The plan seeks, for example, to secure the contributions of nanotechnology to the protection of the environment and climate, to energy supply and to the creation of a knowledge bio-economy. It also aims to achieve environmental and energy-saving in mobility applications (e.g. transport) through nanotechnology.

Japan: Nanotechnology in Japan is mainly covered under the 4th Science & Technology Basic Plan that will run from 2011 to 2015 (but is also in the Basic Environment Plan). This S&T plan encompasses a number of pillars, including green innovation and nanotechnology, which will be supported through investment. Areas of particular interest include energy generation, transmission and storage; energy saving and the protection of the environment; and energy saving in the particular field of information technology.

Korea: The “Third Phase” of the Korean nanotechnology strategy aims to drive economic growth through the convergence of nanotechnology with information nanotechnology, energy technology and biotechnology. In particular, the programme aims to foster the convergence of nanotechnology with other technologies for energy and the environment. Examples of areas of particular interest include helping to resolve the shortage of resources; nanomaterials-based systems for energy production/conversion/storage; nanotechnology for solar cells; next generation batteries using nanostructures; water management using nanostructured membranes; energy harvesting; and submicroscopic technology for power supply.

Netherlands: Nanotechnology has its own roadmap in the Netherlands, in which nanotechnology is expected to have a particular impact on key sectors such as energy, high tech systems and materials and water.

South Africa: The National Nanotechnology Strategy was developed in 2006. The strategy says that nanotechnology should impact social development and industrial competitiveness in the country. Areas of particular interest to the country in relation to green innovation are water and energy.

United States: Solar energy collection and conversion is one of three signature initiatives in the National Nanotechnology Initiative’s 2011 strategic plan. There have been research investments in seven different areas: (1) conversion efficiency (photovoltaic, thermophotovoltaic), (2) solar thermal, thermal conductivity, (3) nanoparticle fluid, heat transfer, (4) thermoelectric, (5) solar fuel, (6) solar characterisation and (7) energy storage (NSET 2011). The initiative received 3.7% (USD 68.8 million) of the overall NNI budget in 2011. The proposed budget for fiscal year 2012 calls for the budget to nearly double and to account for 5.9% of the NNI budget.

Source: Information gathered from presentations at the OECD/NNI Symposium on Assessing the Economic Impact of Nanotechnology, March 2012, nano.gov/symposium and from preliminary results of a WPN project on the Responsible Development of Nanotechnology

In many countries, nanotechnology, and green nanotechnology in particular, is the focus of increased co-ordination and strengthening collaboration between ministries and departments including those involved in science, technology and innovation, education, agriculture, environment, energy and industry and commerce. For example, in Korea, seven governmental ministries have jointly invested about USD 1.9 billion in the nanotechnology programme in the past decade. The Brazilian Inter-Ministries Nanotechnology Committee involves eight different ministries ranging from the Science, Technology and Innovation Ministry to Environment, Energy and Defence. In Germany, seven departments of the federal government have recognised the importance of nanotechnology through the “Nano-Initiative – Action Plan 2015”, a harmonised action framework across all ministries. In Japan, six ministries are involved in

nanotechnology including the Ministry for Education, Culture, Sports, Science and Technology, the Ministry for Agriculture, Forestry and Fisheries, the Ministry of Economy, Trade and Industry and the Ministry of Environment.⁸

Green nanotechnology also has a central role in nanotechnology roadmaps. A recent example of this is seen in the publication *Nanotechnology Research Directions for Societal Needs in 2020* (Roco, 2011). Particular attention is being given to green nanotechnology for several emerging areas: *i*) nanostructured photovoltaics (organic, inorganic); *ii*) artificial photosynthesis for fuel production; *iii*) nanostructures for energy storage (batteries); *iv*) solid state lighting; *v*) thermoelectrics; and *vi*) water treatment, desalination and reuse.

Policies to support green nanotechnology broadly aim to facilitate its development and use for efficient, affordable and safe applications. Sharing and diminishing the costs and risks of development and commercialisation of applications involving green nanotechnology is also a focus for policy intervention through innovative public-private collaborations. Technology policies mainly support R&D investments – increasingly directed towards more applied research although basic research often remains an important area for investment – and supports for small and medium sized enterprises (SMEs).

There is a complex environment around green nanotechnology with fiscal and legislative policies and multiple measures for green growth and more generally for science, technology and innovation. Framing conditions - such as regulation, standards and research, environmental and enterprise policy – strongly influence the development of green nanotechnology for processes or products.

From basic research to technology applications

The potential to commercialise nanotechnology for green innovation has become a particular focus of interest in recent years as nanotechnology research is beginning to be used in multiple concrete applications. With the growing potential of the technology, and in the face of urgent environmental challenges, strategies and investment in nanotechnology have moved from being science-driven to being more application- and challenge-driven, focusing on how technologies, and nanotechnology in particular, could help to address some major national and global challenges. This challenge-driven tendency is apparent in both OECD countries and emerging economies.⁹ The evolving policy landscape of most countries reflects a shift in focus from a concentration on funding basic research towards initiatives focused on improving the links between research and development for nanotechnology, for example stimulating technology transfer and demonstration projects.

There is a direct link made between nanotechnology and its applications in the strategies of many governments, and, where significant levels of investments are being maintained, there is a tendency to move funding to more applied nanotechnology research (see Box 4). In its new Framework Programme for Research and Innovation, “Horizon 2020”, the European Union continues to focus on strengthening the EU’s position in basic science but the largest part of the Horizon 2020 budget will be allocated to science and innovation to address social challenges.

Box 4. Examples of nanotechnology investment

Brazil: Biotechnology and nanotechnology are amongst the eleven areas for strategic investment by the Brazilian government. Between 2004 and 2008 the Ministry for Science & Technology (MCT) invested an average of BRL11.87 million (EUR 4.9 million, USD 6.7 million) per year. In common with most other countries, there is an increasing focus on ensuring successful technology transfer from academia to industry. Brazil's Nanotechnology Programme aims to promote the generation of products, processes and services in nanotechnology, thereby increasing the competitiveness of domestic industry in line with the targets set in the Plan of Action for Science, Technology and Innovation 2007 - 2010 (PACT). Programme actions have included supporting basic research; continuing to support Nanotechnology Research Networks; the creation and maintenance of laboratories to promote integration between networks and research groups with industry; supporting training of teachers and doctors; the implementation of the Brazilian- Argentine Nanotechnology Centre (CBAN); and support for a virtual Brazilian-Mexican Nanotechnology Centre.

China: China has increased its investment in science and technology as a whole, from 1.5% of GDP in 1996 to 2% of GDP in 2010. Investment is expected to reach 2.5% by 2020 under the Medium and Long Term Development Plan 2006-2020 (MLP). Nanotechnology development has been given priority under this initiative and defined as one of twelve 'mega-projects'. These 'mega-projects' and their associated implementation guidelines are intended to support industrialisation related to national socio-economic development within 3-5 years.

The European Union: Under the European Framework Programmes (FP), the EU invested EUR 1.4 billion in NMP (Nanoscience, Nanotechnologies, Materials and New Production Technologies) in the 2003-2006 period and EUR 1.1 billion in 2007-2008, with further growth expected right up until the end of FP7 in 2013. The objectives of the NMP programme are to secure global leadership in key sectors and create added value such as improved safety, security and sustainability. A further European development is the NanoFutures initiative which is a cross-European Technology Platform (ETP) for all nano-related technologies. The High Level Expert Group (HLG) on Key Enabling Technologies (KET), which includes nanotechnologies, presented its policy recommendations to the EC in June 2011: these include addressing the so-called 'Valley of Death', which is the gap between knowledge generation and commercialisation. The HLG has recommended a 'Three Pillar Bridge' strategy for adoption in Horizon 2020 and in the policy instruments related to EU's Regional Policy and the European Investment Bank. The three pillars are: technological research; product demonstration focused on product development; and production based on world-class, advanced manufacturing. A budget of EUR 5.89 billion has been assigned to developing European industrial capabilities in the Key Enabling Technologies sector. Nanotechnology is just one of a number of key enabling technologies which will benefit from this budget.

Germany: Federal funding for nanotechnology research and development in 2010 reached around EUR 400 million with the Federal Ministry of Education & Research (BMBF) increasing investment four fold since 1998. The funding aims have moved forward from those of the 1990's, which focused on basic research, towards more application based funding. The Nano Initiative – Action Plan 2010 provided a unified framework across seven federal ministries to speed up the transfer of nanotechnology research results into industry and to remove barriers to innovation. The German government cites a number of socio-economic objectives for nanotechnology across these seven ministries, including: economic development, resource efficiency, environmental protection, innovative solutions to health problems and international competitiveness of industry. In the Nanotechnology Action Plan 2015, the federal government further focuses strongly on an intensive integration of science and the economy, specifically in the areas of climate and energy, health and nutrition, mobility, security and communication, to ensure effective technology transfer and commercialisation.

India: In May 2007, the Indian government approved the launch of a Mission on Nano Science and Technology (Nano Mission, <http://nanomission.gov.in/>) with a budget of approximately EUR 145 million over 5 years administered by the Department for Science and Technology. This follows on from the more modest Nano Science and Technology Initiative (NSTI) launched in 2001. In the Nano Mission programme, equal importance is given to both fundamental research and the development of products and processes, through the linking of research and industry and Public-Private Partnerships (PPP), particularly in areas highly relevant to challenges facing India, such as safe drinking water and drug delivery. In addition, an important part of this funding is directed towards the development of the human resources required to facilitate a long term sustainable and competitive industry.

Japan: The bulk of nanotechnology funding in Japan is provided through two ministries: the Ministry of Education, Culture, Sports, Science and Technology (MEXT) and the Ministry of Economy, Trade and Industry (METI). These Ministries support basic and applied research through the Japan Science and Technology Agency (JST) and the more industrially focused programmes (including funding of demonstration activities) of The New Energy and Industrial Technology Development Organisation (NEDO). In 2009, nanotechnology represented 5.2% of the budget of the 3rd Science & Technology Basic Plan. Under the 4th Science & Technology Basic Plan, instigated in 2011, fields, such as nanotechnology, are no longer prioritised, having given way to the two broad areas of Life Innovation and Green Innovation.

The United States: The US 2012 Federal Budget provides USD 2.1 billion (EUR 1.6 billion) for its National Nanotechnology Initiative (NNI) representing continuing growth in investment. Since the inception of the NNI in 2001, there has been a cumulative investment of greater than USD 16.5 billion (EUR 12.6 billion). The NNI is an interagency initiative supporting nanoscale science and engineering in participating agencies, such as the Department of Energy. The NNI's vision is '*a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society.*' It also looks to develop a skilled workforce, improve education and develop nanotechnology responsibly. The United States is also addressing the 'Valley of Death' by ensuring US leadership in advanced manufacturing. The President's Council of Advisors on Science and Technology (PCAST) made a number of recommendations to address this, including the launch of an Advanced Manufacturing Initiative, in its report of June 2011. From this, it appears clear that the United States perceives that manufacturing is key to future development and effective competitiveness and, although they remain committed to funding a nano specific programme (NNI), nanotechnologies will also be increasingly incorporated into programmes such as the Advanced Manufacturing Initiative.

Source: OECD/NNI Symposium on Assessing the Economic Impact of Nanotechnology, Background paper: Challenges for Governments in Evaluating Return on Investment from Nanotechnology and its Broader Economic Impact, Eleanor O'Rourke and Mark Morrison, Institute of Nanotechnology, United Kingdom. nano.gov/symposium

The 4th S&T Basic Plan in Japan (2011 to 2015) also illustrates a shift from "R&D prioritisation" to "problem solving", green innovation being a significant pillar of this plan. Since 2001 and the start of its Nanotechnology Development Plan, Korea has also moved its focus from fundamental research in nanotechnology to application driven technology (Dae Sup, 2012). Korea is now entering in the third phase of its plan and emphasising potential applications and solutions of nanotechnology for challenges such as the current pressure on raw resources, energy and the environment.

Investment in environmental health and safety, ethical and social issues and sustainable manufacturing

Efforts to ensure the responsible development of nanotechnology are being made through a growing number of national and international initiatives looking at environmental health and safety (EHS) and ethical and social issues. While nanotechnology for green innovation is increasingly revealing its potential to enhance current technologies or create entirely new solutions, most of these innovations are still in the laboratory and very few products have reached the market to date.

This is due to a number of factors, one being the economic costs which may be incurred in the use of nanotechnology for green innovation. For example, while the application of nanotechnology may save energy and reduce carbon emissions, significant amounts of energy may be involved in producing the component materials.¹⁰ While energy and manufacturing costs are likely to reduce over time as process technologies using nanotechnology are improved and new materials emerge, it will be important to ensure that energy usage, gas emission and other environmental factors associated with the production of materials used in green nanotechnology applications are monitored.

Some nanotechnology applications also raise EHS concerns related to the use and disposal of nanostructures which they employ. The environmental and safety costs of the technology are particularly important to look at when trying to develop and label commercial nanotechnology solutions as "green".

In response to these issues, governments are increasingly including the concept of responsible development in their nanotechnology policies and programmes. Such responsible development aims to stimulate the growth of nanotechnology applications in diverse sectors of the economy, while addressing the potential risks and the ethical and societal challenges the technology might raise. In 2012, the OECD Working Party on Nanotechnology launched a project to inventory activities in several OECD member and non-member countries relating to the responsible development of nanotechnology. Preliminary results of that work show that some countries (e.g. Germany, Korea) have dedicated policies for the responsible development of nanotechnology. Most of the countries responding to the questionnaire fund activities and programmes in the areas of Environmental, Health and Safety (EHS) and Ethical, Legal and Social Implications (ELSI). It was also largely recognised by the participating countries that advances in analysing the potential risks of using nanotechnology can help to reduce uncertainty, thereby encouraging the responsible application of nanotechnology-based innovation.

The United States has been increasing its emphasis on addressing EHS issues (as illustrated by an increase by a factor of 2.5 of its funding for this in the last five years)¹¹ dedicating to EHS about 5% of its budget for nanotechnology and nanosciences (about USD 90 million in 2010) (NNI, 2011). In Europe, 5% of the approximately EUR 600 million spent on nanotechnology annually is dedicated to EHS issues.¹²

Intergovernmental bodies, such as the OECD (in particular, the OECD Working Party on Manufactured Nanomaterials), the World Health Organisation (WHO) and the Food and Agriculture Organization (FAO), are complementing these national and multi-national efforts with a number of programmes dedicated to the responsible development of nanotechnology. Organisations, such as the International Organization for Standardization (ISO), through its Technical Committee ISO TC229, are also contributing to the thinking around the development of frameworks for responsible development and to the development of standards in the area of nanotechnology.

There is also an increased focus on fostering greener manufacturing using nanomaterials, trying to strengthen the link between green nanotechnology, green chemistry and sustainable manufacturing. The United States EPA, for example, has a dedicated project looking at how energy consumption can be minimised and waste/pollution prevented in the manufacturing of nanomaterials and products. The OECD Working Party on Manufactured Nanomaterials also has a dedicated Steering Group on the Environmentally Sustainable Use of Manufactured Nanomaterials.

There are also networks of professionals and institutions engaged with issues such as green synthesis of nanomaterials and advanced manufacturing. The Sustainable Nanotechnology Organization (SNO) is a recently created non-profit, worldwide professional group of individuals and institutions.¹³ Its purpose is to provide a professional forum to advance knowledge of all aspects of sustainable nanotechnology, including both applications and implications.

There are also numerous initiatives to address ethical, legal and social issues (ELSI) for nanotechnology development that base their work on the premise that societal buy-in and public awareness are key to the uptake of nanotechnology innovation. One example is the DaNa project supported by BMBF in Germany, an initiative that seeks to promote transparency and to present the results on nanomaterials and their influence on humans and the environment in an understandable way. The OECD WPN has also undertaken an important body of work on public engagement for nanotechnology (OECD, 2012b).

All these investments, programmes and initiatives aim to create a sufficient pool of knowledge to enable informed policy decisions on responsible and sustainable nanotechnology development, uptake and commercialisation, balancing risks and societal, environmental and economic benefits.

Public – private collaborations: Fostering the transition of green nanotechnology from research to commercialisation

For companies, investment in nanotechnology for green innovation can be costly and without guaranteed returns. Governments are seeking to mitigate these risks by fostering various types of public-private collaborations to enhance the sharing of information, knowledge and resources to make the field advance more efficiently.

There is still a great hesitancy from the private sector to engage in green nanotechnology. This is due to a number of factors, such as the perception of the EHS and ELSI risks associated with the technology (also leading to issues of consumer acceptance), regulatory uncertainty, the lack of maturity of the technology, potential economic costs, market uncertainty and strong competition with incumbent technologies. Nanotechnology often competes badly with existing technologies mainly for two reasons – cost competitiveness and familiarity. For example, Asian (principally Chinese) manufacturers produce large volumes of products at low cost and effectively out-price novel alternatives such as nano-based photovoltaics, the existing high-volume product being considered as “good enough”. All of these factors lead to an environment of uncertainty and a perception of high investment risk.

The possibilities that nanotechnology can offer for green innovation to address some of the major environmental and social challenges have triggered a response from governments that involves trying to reduce risks and uncertainty for companies, thereby aiming to facilitate and accelerate the transfer of nanotechnology innovation to the marketplace. Policies are being put in place to help bridge the gap between research and the market. This market-driven approach includes direct investment in SMEs, for example, but also creating partnerships between governments and public entities and the private sector in order to bring together the resources needed. For example, public/private partnerships are strongly encouraged as part of the plan developed by the Inter Ministries Nanotechnology Committee in Brazil. In Korea, collaboration between industry and academia is being reinforced with the aim of shifting investments from fundamental R&D to more applied research and commercialisation. In India, many nanotechnology institutes have been established in recent years and the government is supporting access by industry to their facilities.

Consortia of industries are also being developed, supported or initiated by public bodies, such as the formation of the NanoBusiness Alliance in the United States and the Nanotechnology Industries Association in Europe. At the R&D and early commercialisation stage, more innovative approaches to pooling risk and knowledge are being seen. There are a number of innovative initiatives that are being put in place based on large consortia of companies and public laboratories and institutions. These give an opportunity for pooling knowledge from corporations, SMEs and public institutions and for integrating and sharing information all along the value chain. Examples of such consortia are Genesis in France, InnoCNT in Germany and NanoNextNL in the Netherlands (see Box 5).

Box 5. Examples of public-private collaborations to foster the commercialisation of nanotechnology applications

Genesis, France: Genesis is a consortium pooling large industrial groups, SMEs and public research laboratories. The partnership is focusing on the design of nanostructured materials, comprising carbon nanotubes in particular, and their applications in fields including transport, energy, environment, and information and communication technologies. The programme is co-ordinated by the chemical company Arkema and has a total budget for R&D of EUR 107 million over the duration of the FP7 funding programme (2007-2013). The consortium aims to strengthen co-ordination between stakeholders.

InnoCNT, Germany: The Innovation Alliance Carbon Nanotubes (Inno.CNT) is a research network in which more than 90 partners from research and industry are involved. It is part of the German government's High-Tech Strategy and is sponsored by the Federal Ministry of Education and Research in its "Materials Innovations for Industry and Society" programme. The total budget of the alliance is EUR 90 million, 50% from the German government (through the BMBF ministry). The overall aim of the initiative is to establish a key market for the technology of carbon nanotubes in Germany, thus creating a global lead in the field of innovative carbon nanomaterials. In addition to basic technologies, the Innovation Alliance CNT focuses on practical applications in the fields of energy and the environment, mobility, lightweight construction and electronics. Major societal and economic challenges of today are found in these areas, including climate change, energy efficiency and supply, mobility and health and safety. Mastering these challenges will require the joint efforts of science and industry. The close networking of all 27 projects of Inno.CNT enables the know-how of all of the partners to be utilised more effectively. In particular, connecting the crossover technologies with the fields of application provides an optimum framework for combining basic research with specific application requirements and market needs, within the project cluster, to develop economically promising solutions. See: www.inno-cnt.de/en/.

NanoNextNL, The Netherlands: NanoNextNL is a consortium for research into micro and nanotechnology of more than one hundred companies, universities, knowledge institutes and university medical centres. The total budget for NanoNextNL is EUR 250 million, half of which is contributed by more than one hundred businesses, universities, knowledge institutes and university medical centres in collaboration and the other half by the government of the Netherlands. NanoNextNL was developed from the proposal "Towards a Sustainable and Open Innovation Ecosystem", which was proposed for the 2009 FES High-Tech Systems and Materials (FES HTS&M). By initiating and supervising research projects, NanoNextNL wants to create a sustainable and competitive open innovation ecosystem that provides new commercial opportunities, innovative products and knowledge infrastructure. NanoNextNL is a selective continuation of parts of the NanoNed and MicroNed programmes. The results and technologies developed in the microscale and nanoscale research being undertaken can be widely used. NanoNextNL will focus on research within ten themes: Energy, Nanomedicine, Clean Water, Food, Beyond Moore (Nano-electronics), Nanomaterials, Bionanotechnology, Nanomanufacturing, Sensors and Risk analysis and impact of nanotechnology. See www.nanonextnl.nl/.

Such consortia involve a large number of companies and facilitate benefit and risk sharing both between public and private entities and between the companies. Consortia also serve to reduce the uncertainty for lead companies bringing a new product to the market when no similar technologies have previously been commercialised, or when the demand for the technology/application is not yet clear.

Policy instruments for the adoption of green nanotechnology: Supporting technology development and influencing demand

Supply and demand-side measures

The policy measures used to create a suitable environment for the adoption of a technological innovation are usually a mix of supply-side and demand-side policies focused on facilitating knowledge transfer; helping to shape the demand for the technology (through, for example, tax incentives, regulation, standards); and fostering research, development and demonstration. The recently published OECD

Science, Technology and Industry Outlook 2012, made a mapping and analysis of the policy measures in place in OECD and emerging economies for transitioning to green innovation. The conclusions show that public support for green innovation mainly takes the form of direct research and development grants to small and medium-sized enterprises (SMEs), but there is also a broad policy mix used to support the adoption of green innovation (OECD, 2012a). How these policies for green innovation, especially demand-side policies, relate to or impact green nanotechnology development is still difficult to picture.

Within supply-side policies, in addition to a focus on R&D activities and in building knowledge-sharing capabilities, increasingly the importance of funding pilot and demonstration projects is being recognised. For nanotechnology to address major environmental and societal challenges, it will be necessary for products based on nanotechnology to be manufactured and used in large volumes. In order to foster this, support schemes involving prototype and pilot manufacturing are being used, as this is the point at which costs and risk are at their highest for such new technological developments. This was recognised in the recent report from the European Commission's High Level Group on Key Enabling Technologies, which urged that more funding be provided for these types of activities (EC, 2011).

The impact of demand-side policies for green nanotechnology innovation is less clear. The OECD Science, Technology and Industry Outlook 2012, identified that a number of targeted demand-side policies, such as public procurement, feed-in tariffs, standard setting and consumer policy to encourage the demand for green technology, are being implemented in many countries but it is not clear whether and how this policy mix is impacting on green nanotechnology. It is also not clear whether demand-side policies have been developed specifically targeted at green nanotechnology.

Demand-side policies specific to nanotechnology may be needed to support the development and commercialisation of green nanotechnology solutions. A number of publications have brought out the issue of "waiting games" around emerging technologies and emerging nanotechnologies in particular, in which producers are reluctant to invest in options for which there is not a clear demand, although there may be in the future if clear product demands are identified. The need for demand to be articulated was highlighted as an issue during the OECD/NNI Symposium on *Assessing the Economic Impact of Nanotechnology* and results from a climate of uncertainty about market perspectives and customer/user demand and requirements (Robinson et al., 2012; Parandian et al., 2012).

As seen in previous sections, efforts are being made to reduce uncertainty and risk through new public-private and company alliances and consortia (such as InnoCNT,¹⁴ Genesis) but there may also be room for interventions to further reduce uncertainty further and to help to articulate the demand. For example, a report from the United States Project on Emerging Nanotechnologies¹⁵ recommended the use of federal procurement to increase the demand for green nanotechnology products (Project on Emerging Nanotechnologies, 2007). Determining demand-side policies will however necessitate the development of possible technology trajectories and analysis of the conditions needed to progress from the proof of principle of an innovation to the introduction and embedding of a product for widespread use in society (Robinson, 2011). Tools to guide decisions include market analysis and forecasting and the use of scenarios in techniques such as technology assessment.

Related role of policies supporting green chemistry

Green nanotechnology is closely interconnected with a field which is already receiving significant policy attention: green chemistry.

A recent report from the OECD looked in depth at the role of government policies in the adoption of green chemistry and its role in sustainable manufacturing. Results from a questionnaire, to chemical industry representatives from OECD countries and beyond, report the views of companies on the current

state of green chemistry in industry and the impact and role of government policies in the area. Responses indicated that traditional regulatory measures and product standards have an important influence on the respondent firms involvement with green chemistry. However, three forms of government expenditures (procurement, prizes and grants) were seen as being less influential than regulation and standards. This may reflect the perception that such measures were seen to be less prevalent. The report highlighted that several studies had tried to illuminate the scientific, policy and economic factors that both drive and hinder green chemistry innovations but that more information and analysis is needed to understand the dynamics of green chemistry innovation and commercialisation, especially from the industrial perspective (OECD, 2012c).

There are links that can be made between green chemistry to nanotechnology (see Box 3) by looking, for example, at how policy supports for the development of green chemistry have impacted innovation in nanotechnology and *vice versa*.

If links can be made between green nanotechnology, green chemistry and sustainable manufacturing; green nanotechnology raises its own particular issues in matching policies to specific barriers to the adoption of nanotechnology (e.g. environmental externalities, access to capital) (ACS Green Chemistry Institute/ Oregon Nanoscience and Microtechnologies Institute, 2011).

Beyond green nanotechnology: Convergence of green technologies

An increasing trend in science, technology and innovation strategies is to consider nanotechnology not only on its own but in convergence with other technologies. At the recent OECD/NNI Symposium on Assessing the Economic Impact of Nanotechnology, it was noted that it is from the integration of different key enabling technologies that it is most likely that their anticipated potential will be achieved.¹⁶ One example of policies for the integration of nanotechnology with other technologies can be found in the third phase (2011-2020) of the Korean nanotechnology strategy. It highlights strategies for nanotechnology convergence in energy and environmental areas in Korea, especially the convergence of nanotechnology with information technology, energy technology and biotechnology.

Having considered the policies in place for nanotechnology for green innovation, Chapter 3 looks at the potential impact of green nanotechnology.

CHAPTER 3: THE IMPACT OF GREEN NANOTECHNOLOGY

There are significant potential markets for green nanotechnologies but very few products have been commercialised to date. It is expected that the contribution of nanotechnology will be significant but that one or two more decades might be needed to fully realise the market potential of green nanotechnology.

In the process of producing and using green nanotechnology products, in addition to direct impacts, there are likely to be a series of indirect effects, including spillovers to third parties and other impacts on supply chains, impacts on the environment and energy usage. The costs associated with the application of green nanotechnologies need to be offset against their beneficial impacts, taking into account such factors as the timing and distribution of various benefits and costs, interest rates, opportunity costs, and the relative advantages of green nanotechnologies compared with conventional applications.

Not all of the benefits and costs will be easily measurable. As the technology is being developed, greater efforts are being made to find ways of assessing or tracking the impact of nanotechnology on specific policy objectives such as green growth. This is a very challenging task. Methodologies being considered for use in assessing the impact of green nanotechnology need to value the full range of potential impacts - economic, environmental and societal implications - which the technology might provide. The risks of using new green nanotechnologies need to be considered relative to the risks in using current technologies (which may be highly energy intensive, use toxic materials or have negative environmental impacts) and valued against the human and environmental costs of not effectively addressing key global challenges (such as reducing carbon emissions or providing potable water).

The information for this section was largely gathered from the OECD/NNI Symposium on *Assessing the Economic Impact of Nanotechnology*, held in March 2012 in Washington DC, United States.

Challenges in assessing the impact of green nanotechnology

Green nanotechnology is generating significant interest amongst governments seeking to recover from recent economic crises and to address pressing environmental needs. While investments to develop the field are being made, as seen in the previous chapter, it is still difficult for policy makers to assess: *i)* to what level those investment are sufficient and well-targeted and what return can be expected from them; *ii)* the impact of nanotechnology on social and economic objectives such as green growth. It is increasingly important for policymakers to have evidence-based rationales for allocating scarce resources in a time of fiscal constraint and at a time when OECD countries and emerging economies are also confronting the need for new sources of growth and new jobs and skill creation.

General challenges to assessing the impact of nanotechnology

Some of the numerous issues which make assessing the impact of nanotechnology difficult include the following:

- There are no conventional definitions or classifications for nanotechnology, nor definitions of a nanotechnology product, a nanotechnology process or a nanotechnology company. It is in general not clear to what extent organisations, such as companies, universities and research institutions,

are involved in exploiting and developing nanotechnology. Definitions are central to understanding the nature of the contribution of nanotechnology and to enable in data collection;

- Measuring the impact of nanotechnology is made more complex by its multipurpose nature. Nanotechnology can be fundamental to a product and give it its key functionality, or it can be ancillary to the value chain and constitute a small percentage of a final product; or it may not even be present in the final product, only affecting the process leading to its production. For a complete impact assessment it is necessary to look not only at the final product containing nanotechnology but also the potential impact of nanotechnology all along the value chain;
- The sheer number of applications of nanotechnologies across all technology sectors, and their enabling nature, creates a complex and fractured landscape for analysis;
- Gathering information from industry can be difficult because of sensitivity surrounding nanotechnology products.

The nanotechnology policy landscape is evolving as countries employ more challenge- and manufacturing-driven, rather than science-driven, policies and strategies. The use of non-specific, rather than nanotechnology specific, funding strategies and policies is an important factor to consider when assessing specific economic impacts such as return on investment. The structure of the funding of nanotechnology by governments is relevant to measuring value for money, i.e. measuring the amount and type of funding and investment which has gone into nanotechnology and the resultant economic impacts. Where a funding programme is not exclusively directed towards nanotechnology (for example, a health programme focused on a grand challenge that may not be technology specific but which includes nanobiotechnology or advanced nanomaterials), it can be difficult to identify the final value derived from the ‘nano’ investment. This may introduce difficulties in comparing data collected on input and investment and the economic impact related to nanotechnology.

Green nanotechnology in a complex policy landscape

The development of green nanotechnology is impacted by framing conditions such as regulation, standards and non-technological policies. Its applicability across numerous economic sectors, its potential to impact all along the product value chain and its enabling nature make the contribution of nanotechnology to green innovation difficult to determine. In order to get a clear picture it would be necessary to disentangle the impact of nanotechnology from a whole host of other factors, linking data on nanotechnology developments to economic data.

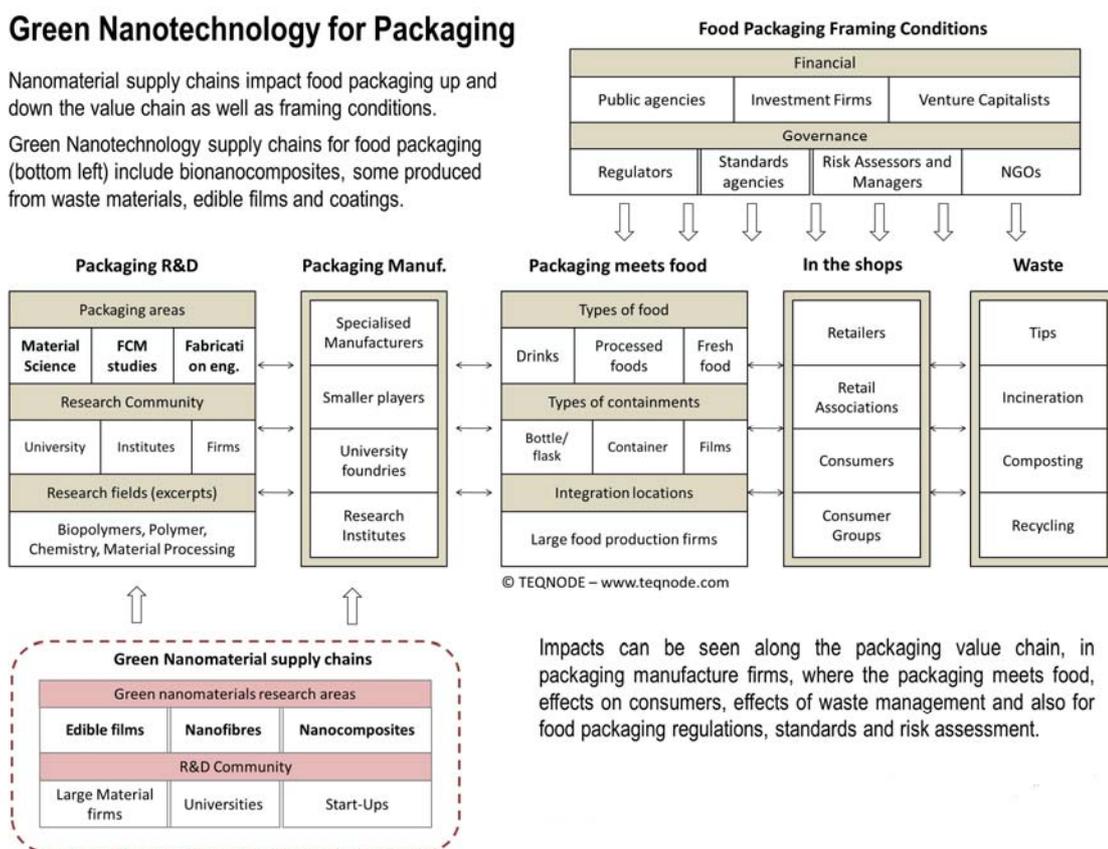
One example of the complexity of analysing the impact of nanotechnology is seen in nano-improved lithium ion batteries for electric vehicles. The need to reduce reliance on fossil fuels and to limit greenhouse gas emissions is driving the mass manufacture of reliable and fit-for-purpose electric vehicles. One core component is the battery, which is currently limited by power density (electric vehicles have a range of approximately 100-200 km between charges) and charging rates (a full recharge can take up to eight hours), both of which limit consumer satisfaction. In undertaking an impact analysis, the question to be addressed is how much added value the nano-battery adds to the final product. Also of importance is the impact analysis of the nano-enabled battery in the context of the nanotechnology input in many other systems and components of the green car (e.g. for weight reduction through advanced nanomaterials, decreased rolling resistance and energy scavenging).

It is easier to define inputs such as the starting materials being used. These can often be identified through an examination of publications and patents in which they are categorised as nanomaterials. The collection of data at later stages of the value chain becomes reliant on less quantitative methods. The direct

economic impact of mass-producing a battery that addresses such issues could be significant. The indirect economic impacts are likely to include energy-related impacts (e.g. the electricity used to recharge the batteries can come from a variety of sources including nano-enabled renewables) and lower pollution (reducing effects on human health and the environment). Potential negative impacts also need to be considered, such as displacement of jobs from the oil and gas industry.

To carry out a true cost-benefit analysis, the impacts of the nanotechnology must be extracted from the total impacts of nanotechnology and all other interventions. These can include the cost of batteries and the electric vehicles (which could limit market penetration); the cost of creating a viable infrastructure of charging stations; legislation (which may drive forward new solutions that may or may not include nanotechnology); consumer acceptance of the electric vehicle (which may or may not meet all the requirements of the potential customer); and competing technologies including biofuels and hydrogen fuel cells (which may attract both fiscal incentives and investment by large industry). Understanding the influence of each of these is important in identifying the impact of nanotechnology. Thus a very good knowledge of the specific value chain for each green nanotechnology application is needed. Such knowledge of value chains necessitates an understanding of the sequence of interactions between suppliers, manufacturers, distributors and consumers and the influence of framing conditions such as the policy environment. For example, green nanomaterials for the food sector have impacts along the packaging value chain and are influenced by a number of external framing conditions (see Figure 3).

Figure 3. Green nanotechnology for packaging



Source: Adapted from Robinson DKR (2013), "Indications of socio-economic impacts of nanotechnologies", forthcoming chapter in the edited volume of the fourth annual conference of the Society for the study of Nanoscience and Emerging Technologies (S-NET). www.utwente.nl/igs/conference/2012_snet_conference/

It can also be considered that, for countries to fully benefit economically from a nanotechnology development, it is necessary for all parts of the value chain to be located in one place, i.e. the means to research, develop and produce (or exploit) the R&D. For example, if the underlying technology for a water treatment system was developed in country A, but manufactured in country B, the manufacturing country B would reap a number of direct (such as market share, jobs, financial return) and indirect (such as improved water quality and reduced environmental burden) economic benefits from the original investment by the government of country A. Thus it is possible that, without an existing indigenous nanotechnology industry base, countries may be unable to derive significant economic impacts of their nanotechnology investments and an impact assessment will show a low return. It is not uncommon for the patents on which future green nanotechnology applications are based to originate mainly in developed countries, while the use of these patents (meaning the manufacturing of solutions based on green nanotechnology) happens in emerging economies such as China. Thus, the investments made in developed countries may only result in economic and societal impacts, such as jobs, in emerging economies.

Examples of nanotechnology valuation methodologies

While there are significant challenges in assessing the value of nanotechnology, some assessment methodologies have been developed.

Factors to be considered in valuing green nanotechnology

Simple analyses of the economic contribution of green nanotechnologies would consider the net costs of technological development and market entry relative to the value of the outputs and outcomes achieved, taking into account considerations of time and perspective.

The net costs include such inputs as public R&D investment, knowledge development costs and the costs of facilities, private industry R&D costs and the cost of prototyping, testing, commercialisation, production and marketing.

The outputs from such expenditures can include contributions to scientific and other knowledge, development of generic or specific technologies, creation and use of intellectual property (including patents and licenses), the development of standards and the spin-off and start-up of new companies. These outputs can have intermediate economic value but the clearest economic impacts are through outcomes such as profitable sales from new products, increased productivity and other process improvements, cost savings, employment and wage generation, taxation and benefits to consumers and users. These outcomes can lead to developmental and public benefits including contributions to national and regional gross domestic product, improved competitiveness and balance of trade and environmental and other societal benefits.

There can also be strategic benefits in the use of nanomaterials, for example to reduce reliance on rare metals and materials sourced from overseas locations. However, the relative weight of benefits and costs of a new technology may vary according to whether the perspective is that of a producer, competitor, customer, worker, industry, region, or country (i.e. according to perspective).

Comparing green nanotechnology with incumbent technology

The United Kingdom Department for Environment, Food and Rural Affairs (DEFRA) methodology aims to assess the value of nanotechnology in comparison with an incumbent technology and uses life cycle assessment tools. A well-elaborated example using the DEFRA methodology is provided in a study

by Walsh et al. (Walsh, 2010). This study describes a methodology for estimating the net value-added of a nanotechnology innovation, which is defined as the difference between the value-added of the nano-enabled product and that of the comparable incumbent product. It assumes that there are conventional incumbent products against which new nanotechnology products can be matched.

The net value-added is comprised of three elements: producer surplus (sales less costs) plus consumer surplus (consumer value less price); plus other externalities (net benefits to third parties). A multi-step process is employed which involves:

- Defining the nano-enabled product;
- Identifying its use and function;
- Identifying a comparable incumbent product;
- Determining the production costs of the nano product and its comparator;
- Determining sales prices;
- Identifying the effect of the nano-enabled product on the market;
- Determining externalities (including net environmental benefits and R&D spill-overs) and
- Calculating producer surplus, consumer surplus and externalities; and
- Identifying market scenarios in which the incumbent product is replaced with the new product.

The market scenarios have variations e.g. whether the market size is unchanged or increased; whether functionality of the product is increased; whether a consumer surplus results in price declines; and whether there is improved performance by the nano-product relative to the incumbent. The approach also allows for geographical allocations of producer surplus and for specific externalities (e.g. where the location of the production differs from the location of consumption).

The model considers the “phase-in” time of the product (diffusion time).¹⁷ Discount rates are applied to adjust future expected cash flows to present values. The rate is comprised of two parts: a normal (or risk free) component accounting for expected inflation; and a premium that discounts the probability that the product may not successfully reach the market.

Walsh and colleagues applied their approach to several green nanotechnology cases studies, including nano-enabled food packaging, thin-film photovoltaics, fuel catalysts, amperometric electrochemical gas sensors, nano-enabled anti-fouling paints and nZVI technology (Walsh et al., 2010). The case studies, which took a national perspective, illustrated that net economic benefits are relatively small where the nano-enabled product has limited advantages over incumbent products and market size is unchanged. Larger benefits accrue where the nano product reduces costs compared with the incumbent, markets are expanded and diffusion is relatively rapid.

The national context of the case studies was important for the analysis. For the United Kingdom, economic externalities are reduced for some technologies because R&D, materials production or manufacturing take place overseas. In the main, net benefits were estimated for United Kingdom markets (which are a relatively small share of potential global markets). Environmental benefits and costs outside of the United Kingdom were not included in the analyses (although they were mentioned).

The authors recognised that there are significant uncertainties in the forecasts of markets and nanotechnology penetration. It was also noted that a monetary value often cannot reliably be placed on environmental impacts and that current evidence is inconclusive on some potential environmental impacts. Subsequent detection of health or environmental damage would negatively affect the benefit-cost ratios calculated.

This methodology was also used in Korea to assess the economic impact of the use of nanotechnology in light-emitting diodes (LEDs). The analysis showed a high value of externality for electricity saving in comparison with the incumbent technology. The study also highlighted that the scope for the use of nanotechnology in the production of LEDs made analysis difficult, an effect associated with the lack of a clear definition or description of the contribution of nanotechnology to a product.¹⁸

In trying to assess the value of nanotechnology, it is important to keep in mind that benefits to producers and consumers may not necessarily maximise societal benefits. End users, when they analyse the situation from their own specific economic perspectives, will typically consider the price-performance parameters of a new technology such as nanotechnology when compared with other alternatives. Direct purchasing, capital and operational costs will be of concern. Depending on the user and application, the societal impacts of the product or process may or may not be of particular interest compared with specific factors of performance and functionality. For example, a medical device could be made smaller with increased operating life by incorporating a nano-enabled printed battery sheet. A user needing this medical device is likely to focus on those improved performance characteristics, including reliability and accuracy and may well decide to pay a premium for them. How this device is made and how it can be disposed of or recycled after use may or may not be of concern at the point of purchase. Similarly, for a novel nano-enabled insulating window glass, a customer will most likely be interested in the cost of purchase and installation and in the savings in energy costs over multiple years compared with conventional window units. Considerations of the energy required to manufacture and recycle the new nanotechnology-based units may, or may not, be influential in the decision to adopt the technology. Such spill-overs are typically not in the control of the producer or consumer and an assessment of them may not feature prominently in the purchasing or adoption decision. The extent to which these externalities are considered by individual purchasers in the evaluations they make of the relative advantages or disadvantages of green nanotechnologies will vary, although they may be influenced by the availability of information, regulatory provisions, standards and the adoption of codes of practice related to sustainability.

NOTES

¹ WPN case studies on Nanotechnology for Green Growth are in development and should be released in autumn 2013.

² US Patent 6469089

³ Information from Fraunhofer, for more information see [:www.fraunhofer.de/en/press/research-news/2012/november/visible-light-communications.html](http://www.fraunhofer.de/en/press/research-news/2012/november/visible-light-communications.html)

⁴ Information from the Innovation Alliance Carbon Nanotubes, for more information see: www.inno-cnt.de/en/

⁵ Early estimates of the amount of energy required to produce single-walled carbon nanotubes (SWCNT) were relatively high (due to the high temperatures and pressures required) resulting in significant increases in carbon dioxide emissions (Isaacs, 2006) (Agboola, 2007). More recent estimates (Gutowski, 2010) continue to suggest wide disparities in energy requirements for SWNT manufacture, depending on the method used, although large variations are reported for what seem to be similar processes. Using a prospective Life Cycle Assessment (LCA) approach, Wender and Seager 2011) argue that the intensive energy requirements for the large-scale manufacture of SWCNT-enabled lithium-ion batteries currently make them impracticable.

⁶ For example, nanomaterials such as nZVI (nano metallic iron) are effective in absorbing and remove groundwater pollutants (Kanel, 2005) (Li, 2006). Yet, there are concerns about potential EHS impacts, including the toxicity of partially-remediated compounds and downstream entry into water sources and plant and food chains (Royal Society, 2004 ; Grieger, 2010 ; Müller and Nowack, 2010). Similarly, quantum dots – extremely small particles of semiconductor materials with customisable electrical and optical features - have potential green applications in low energy lighting and more efficient solar cells. Quantum dots are often comprised from cadmium and selenium and they may, under certain conditions, release toxic compounds during use or on disposal (Mahendra, 2008 ; Botrill and Green, 2011).

⁷ Information gathered from preliminary results of the OECD WPN project on the Responsible Development of Nanotechnology.

⁸ Information gathered from presentations at the OECD/NNI Symposium on Assessing the Economic Impact of Nanotechnology, March 2012, see nano.gov/symposium and from preliminary results of a project from the OECD WPN on the Responsible Development of Nanotechnology.

⁹ Information gathered from presentations at the OECD/NNI Symposium on Assessing the Economic Impact of Nanotechnology, March 2011, nano.gov/symposium

¹⁰ Early estimates of the amount of energy required to produce single-walled carbon nanotubes (SWCNT) were relatively high (Isaacs, 2006); another study concludes that two of the most economically-viable methods of carbon nanotube production were energy intensive (due to the high temperatures and pressures required) and would thus add significant carbon dioxide emissions (Agboola, 2007). More recent estimates (Gutowski et al., 2010) continue to suggest wide disparities in energy requirements for SWNT manufacture, depending on the method used although large variations are reported for what seem to be similar processes.

- 11 OECD/NNI Symposium on Assessing the Economic Impact of Nanotechnology, 27-28 March 2012. Presentation from Altaf Carim, Assistant Director for Nanotechnology, Office of Science and Technology Policy, Executive Office of the President, United States, nano.gov/symposium.
- 12 Information gathered from presentations at the OECD/NNI Symposium on Assessing the Economic Impact of Nanotechnology, March 2012, nano.gov/symposium.
- 13 For more information see: www.susnano.org/governance.html.
- 14 For more information see www.inno-cnt.de/en/.
- 15 For more information see www.nanotechproject.org/.
- 16 Information gathered from presentations and discussion at the OECD/NNI Symposium on Assessing the Economic Impact of Nanotechnology, March 2012, nano.gov/symposium.
- 17 An S-curve model is used.
- 18 Information gathered from a presentation by Prof. Chang-Woo Kim, Director-General National Nanotechnology Policy Center (NNPC), Korea Institute of Science and Technology Information at the OECD/NNI Symposium on Assessing the Economic Impact of Nanotechnology, March 2012, nano.gov/symposium.

REFERENCES

- ACS Green Chemistry Institute and the Oregon Nanoscience and Microtechnologies Institute (2011), *Green Nanotechnology Challenges and Opportunities*, White Paper, www.onami.us/PDFs/nano-whitepaper.pdf.
- Agboola, A.E., Pike, R.W., Hertwig, T.A., and Lou, H.H. (2007). Conceptual design of carbon nanotube processes. *Clean Technologies and Environmental Policy*, Vol. 9, Issue 4, pp. 289-311.
- Botrill, M. and M. Green (2011), "Some aspects of quantum dot toxicity", *Chemical Communications*, Vol. 47, No. 25, pp. 7039 -7050.
- Dae Sup, S., C. W. Kim, P.S. Chung and M.S. Jhon (2012), "Nanotechnology Policy in Korea for Sustainable Growth", *Journal of Nanoparticle Research*, Vol. 14, No.854, Springer.
- EC (2011), *Final Report from High Level Group on Key Enabling Technologies*, http://ec.europa.eu/enterprise/sectors/ict/files/kets/hlg_report_final_en.pdf.
- Grieger, K.D., A. Fjordboge, N.B. Hartmann, E. Eriksson, P.L. Bjerg and A. Braun (2010), "Environmental benefits and risks of zero-valent iron nanoparticles (nZVI) for in situ remediation: Risk mitigation or trade-off?" *Journal of Contamination Hydrology*, 118, 3-4, 165-83.
- Gutowski T.G., J.Y.H. Liow and D.P. Sekulic (2010), "Minimum exergy requirements for the manufacturing of carbon nanotubes", *IEEE International Symposium on Sustainable Systems and Technologies*, Washington, DC. May 16-19.
- IEA (2011), *World Energy Outlook 2011*, OECD Publishing, Paris
- Isaacs, J.A., A. Tanwani, M. L. Healy (2006), "Environmental assessment of SWNT production", *Electronics and the Environment, Proceedings of the 2006 IEEE International Symposium on Electronics and the Environment*, Scottsdale, AZ. May 8-11, pp. 38-41.
- Kanel, S.R, B. Manning, L. Charlet and H. Choi (2005), "Removal of arsenic (III) from groundwater by nanoscale zero-valent iron", *Environmental Science and Technology*, Vol. 39, No. 5, pp. 1291-1298.
- Li, X.Q., D.W. Elliott and W. Zhang (2006), "Zero-valent iron nanoparticles for abatement of environmental pollutants: Materials and engineering aspects", *Critical Reviews in Solid State and Materials Sciences*, Vol. 31, No. 4, pp. 111-122.
- Mahendra, S., H. Zhu, V.L. Colvin and P.J. Alvarez (2008), "Quantum dot weathering results in microbial toxicity", *Environmental Science and Technology*, Vol. 42, No.24, pp. 9424-9430.
- Müller, N. and B. Nowack (2010), "Nano zero valent iron – the solution for water and soil remediation?" *ObservatoryNANO*, www.observatorynano.eu (accessed 19 February 2012).
- NNI (2011), National Nanotechnology Initiative Environmental, Health, and Safety Research Strategy, National Science and Technology Council (NSTC), United States.

- OECD (2012a), “Transitioning to green innovation and technology”, *OECD Science, Technology and Industry Outlook 2012*, OECD Publishing, http://dx.doi.org/10.1787/sti_outlook-2012-en
- OECD (2012b), *Planning Guide for Public Engagement and Outreach in Nanotechnology*, OECD, Paris, www.oecd.org/sti/biotechnology/policies/49961768.pdf
- OECD (2012c), “The Role of Government Policy in Supporting the Adoption of Green/Sustainable Chemistry Innovations”, *OECD Environment, Health and Safety Publications Series on Risk Management*, No 26. [http://search.oecd.org/officialdocuments/displaydocumentpdf/?cote=env/jm/mono\(2012\)3&doclanguage=en](http://search.oecd.org/officialdocuments/displaydocumentpdf/?cote=env/jm/mono(2012)3&doclanguage=en).
- Parandian, A., A. Rip and H. te Kulve (2012), “Dual dynamics of promises, and waiting games around emerging nanotechnologies”, *Technology Analysis & Strategic Management*, Vol. 24, No. 6, pp. 565-582, www.tandfonline.com/doi/pdf/10.1080/09537325.2012.693668
- Project on Emerging Nanotechnologies (2007), “Green Nanotechnology: It’s Easier Than You Think”, http://eprints.internano.org/68/1/GreenNano_PEN8.pdf.
- Robinson D.K.R. (2013), "Indications of socio-economic impacts of nanotechnologies", forthcoming chapter in the edited volume of the fourth annual conference of the Society for the study of Nanoscience and Emerging Technologies (S-NET), www.utwente.nl/igs/conference/2012_snet_conference/
- Robinson, D.K.R., C. May, C.E. Bolton, Z.R. Yousef, E.C. Conley, O.F. Rana et al. (2012), “Waiting games: innovation impasses in situations of high uncertainty”, *Technology Analysis & Strategic Management*, Vol. 24, No.6, pp. 543-547, <http://dx.doi.org/10.1080/09537325.2012.693661>.
- Robinson, D. K.R (2011), “Value chains as a linking-pin framework for exploring governance and innovation in nano-involved sectors: illustrated for nanotechnologies and the food packaging sector”, *European Journal of Law and Technology*, Vol. 2, No.3, <http://ejlt.org/article/view/104/166>
- Roco, M.C., C.A. Mirkin and M.C. Hersam (2011), “Nanotechnology Research Directions for Societal Needs in 2020: Retrospective and Outlook”, Springer, Berlin and Boston.
- Royal Commission on Environmental Pollution (2008), “Novel Materials in the Environment: The Case of Nanotechnology”, Presented to Parliament, November 2008, Cm 7468, HMSO, London.
- Royal Society (2004), “Nanoscience and nanotechnologies: Opportunities and uncertainties”, Royal Society and the Royal Academy of Engineering, London.
- Schiederig, T., F. Toetze and C. Herstatt (2011), “What is Green Innovation? A quantitative literature review”, *Working Papers / Technologie und Innovations Management*, Vol. 63, Technische Universität Hamburg-Harburg, <http://hdl.handle.net/10419/55449>
- Walsh, B., P. Willis and A. MacGregor (2010), “A comparative methodology for estimating the economic value of innovation in nanotechnologies”, a report for DEFRA, Oakdene Hollins, Aylesbury, United Kingdom.
- Wender, B.A. and T.P. Seager (2011), “Towards Prospective Life Cycle Assessment: Single Carbon Nanotubes for Lithium-ion Batteries”, *2011 IEEE International Symposium on Sustainable Systems and Technology (ISSST)*, Chicago, IL., May 16-18.

WHO/UNICEF (2010), *Progress on Sanitation and Drinking Water*, 2010 Update, WHO and UNICEF, Geneva.

Xiangwen Zhou, Y. Zhu and J. Liang (2010), “New Fabrication and Mechanical Properties of Styrene-Butadiene Rubber/Carbon Nanotubes Nanocomposite”, *Journal of Materials Science & Technology*, Vol. 26, Issue 12, pp.1127-1132,
www.sciencedirect.com/science/article/pii/S1005030211600121.