The Next Production Revolution
Implications for Governments and Business

PART I

## Chapter 4

# Tapping nanotechnology's potential to shape the next production revolution

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*Nanotechnology is a general-purpose technology (GPT), which enabled numerous product and process innovations, as well as productivity and sustainability enhancements in nearly all existing market sectors. Nanotechnology has the potential to enable further innovations and establish new market sectors in the near future. Continuing advancement of nanotechnology requires substantial investment in research and development (R&D) and commercialisation. Investment should be supported by inter- and intra-national collaborations, providing virtual research infrastructures, which allow the sharing of otherwise prohibitively expensive equipment and foster interdisciplinary research ecosystems that are inclusive of academia, governmental research and large and small companies, in order to fully harness nanotechnology's innovation power in all existing and in potentially new industry sectors. Novel business and innovation-funding models should be developed, which account for the increasing multidisciplinarity and the advancing digitalisation of innovation. Regulatory hurdles to the commercialisation of nanotechnology should be removed.*

## Introduction

Nanotechnology is increasingly used in production processes and manufactured products. For example, nanotechnology enables the replacement of energy-hungry production processes (such as the fabrication of solar cells in zone-melting processes) with low-cost processes (such as roll-to-roll printing of solar cells in ambient air). Nanotechnology can also underpin cheap single-use products (such as lab-on-a-chip diagnostics).

Expectations that nanotechnology could play a larger role in the productive sector, and in science, are based on the view that nanoscience, and its application in nanotechnology, represent the ultimate breakthrough in controlling matter on a length-scale where the shape and size of assemblies of individual atoms determines the properties and functionalities of all materials and systems, including those of living matter.

In the short and medium term, nanotechnology will continue to improve existing products and production processes. Entirely new products and processes from nanotechnology-based innovations may arise in the long term. In both cases, productivity could increase, and demand for skilled workers will rise. Greater understanding of nanometre-scale phenomena will be needed, requiring investments in basic and applied science.

In order to achieve the economic and societal benefits that nanotechnology could enable, policy makers should consider implementation of some specific policies. This chapter discusses and suggests the following policies:

- investment in research and development (R&D) and commercialisation of nanotechnology
- support of and investment in virtual research infrastructures, which allow the sharing of otherwise prohibitively expensive R&D equipment and foster a collaborative research environment that is inclusive of academia, governmental research and large and small companies
- fostering of interdisciplinary research ecosystems
- support of novel business and innovation-funding models, which need to take account of the increasingly collaborative nature of R&D for complex inventions, as well as the advancing digitalisation of research and production processes
- recognition and timely removal of regulatory barriers to innovation in nanotechnology, including regulatory uncertainties.

### *From scientific curiosity to disruptive technology*

The term "nano" describes a length-scale (i.e. $1 \times 10^{-9}$ m to $100 \times 10^{-9}$ m. A standard sheet of paper is about 100 000 nanometres thick). "Nanotechnology" is a collective term for all technological effects and material properties that are enabled by scientific phenomena occurring at the length-scale of a billionth of a metre. Interactions at this so-called "nanoscale" are of key importance to life and the material world. The nanoscale is the realm where individual atoms, which do not have any material properties in their own right, form bonds with other atoms. This creates the smallest (nanoscale) functional units of materials, whose properties, functionalities and processes can be observed in the inorganic and biological world around us.

The widest definition of nanotechnology therefore includes all phenomena and processes occurring at this length-scale, spanning a broad range of developments from quantum-effect computing (in the discipline of physics), to invisible materials (in solid state chemistry), to artificial tissue and biomimetic solar cells (in biology), to theranostic actuators used in medicine (enabled by the nano-electro-mechanical systems created in the engineering disciplines).

Through the ability to understand and design material properties at the atomic scale, nanotechnology is a key enabler of many advanced production processes and manufactured products. For example, nanotechnology can enable the replacement of energy-hungry production processes (such as the fabrication of solar cells in zone-melting processes) with low-cost processes (such as roll-to-roll printing of solar cells in ambient air). Nanotechnology provides the technical solution that makes flexible computer screens possible. And nanotechnology can underpin new advanced single-use products (such as lab-on-a-chip diagnostics).

Nanotechnology is a general-purpose technology (GPT) (Helpman, 1998; Lipsey, Carlaw and Bekar, 2005). It has often been predicted that nanotechnology could initiate the next industrial revolution. Nanotechnology is expected to have a significant (in some cases, disruptive) impact in all existing industrial sectors, and to harbour the ability to enable the creation of entirely new sectors. As it develops, nanotechnology will enter a widening range of uses and require complementary technologies and institutions.

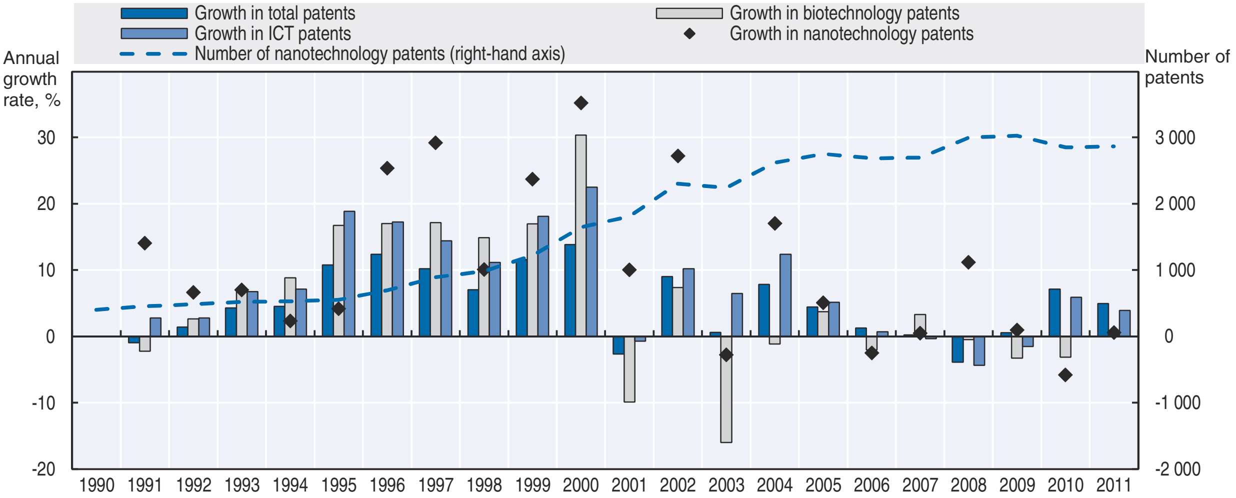
In the 1980s, science- and technology-foresight studies envisaged rapid advancements from the initial discovery of material control on the nanometre scale, to the ultimate creation of any complex functional system from its smallest building blocks (Drexler, 1986).

Figure 4.1 shows repeated episodes of growth in the number of nanotechnology patents (black diamonds), several times larger than observed for comparable enabling technologies, such as biotechnology (grey bars) and information and communication technology (ICTs) (light blue bars). Together with the overall increase in the number of nanotechnology patents filed between 1990 and 2011 (dashed blue line, right hand axis) the figure illustrates that the diverse field of nanotechnology repeatedly spurred a hype-like approach to research and technology patenting. Figure 4.2 provides more detail on the sub-areas of nanotechnology that have given rise to an increased interest in specific nanoscale-based phenomena.

Figure 4.2 illustrates the wide range of nanotechnology applications for which patent protection has been sought. The figure also shows change over time in the nine nanotechnology sub-areas assigned by patent offices for classification purposes. While "nano-optics" and "information processing, storage and transmission" were the dominant nanotechnology sub-areas in 1990, "nano-composites" and "manufacture or treatment of nano-structures" were the largest sub-areas in 2011. The percentages displayed in Figure 4.2 are based on the counts of filings in IP5 patent families, according to earliest filing date.

Figure 4.1. **Evolution of patents in nanotechnology, biotechnology and ICT, 1990-2011**

Annual growth rates, IP5 patent families

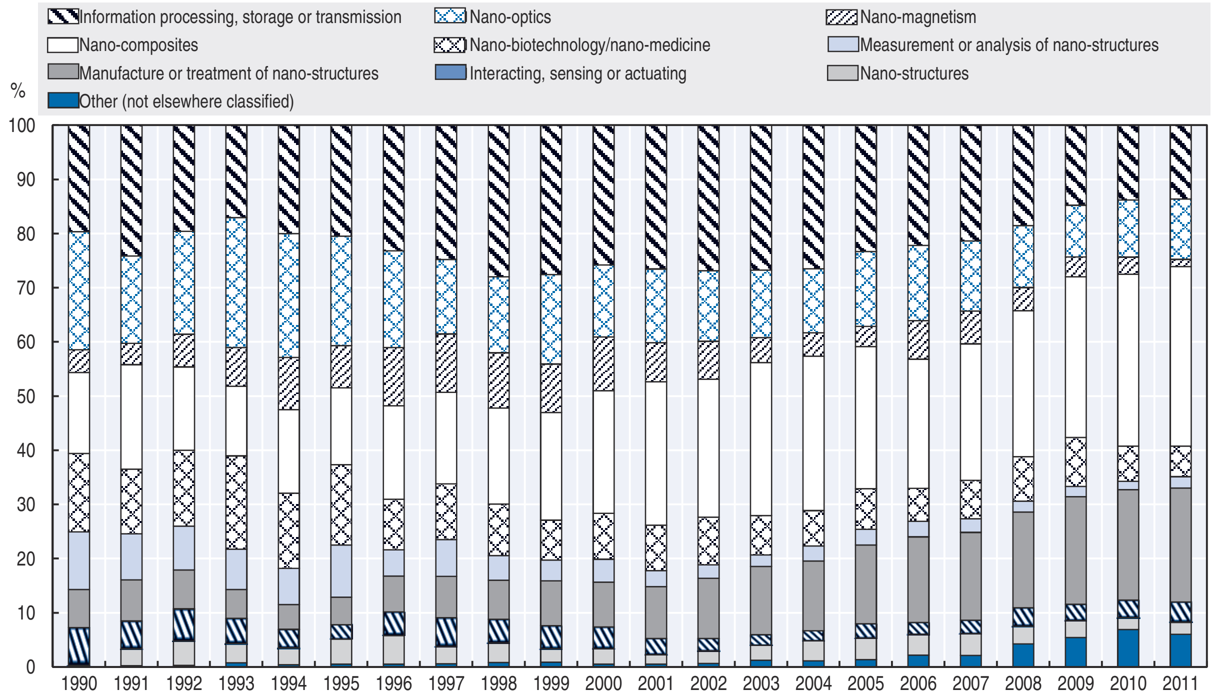


*Source:* OECD (2016b), *STI Micro-data Lab: Intellectual property* database, *http://oe.cd/ipstats* (accessed October 2016).

StatLink *http://dx.doi.org/10.1787/888933473820*

Figure 4.2. **Development of nanotechnology sub-areas, 1990-2011**

Share of sub-areas in nanotechnology patents, IP5 patent families



*Note:* n.e.c. = not elsewhere classified.

*Source:* OECD (2016b), *STI Micro-data Lab: Intellectual property* database, *http://oe.cd/ipstats* (accessed October 2016).

StatLink *http://dx.doi.org/10.1787/888933473830*

## The changing face of a revolutionary enabling technology

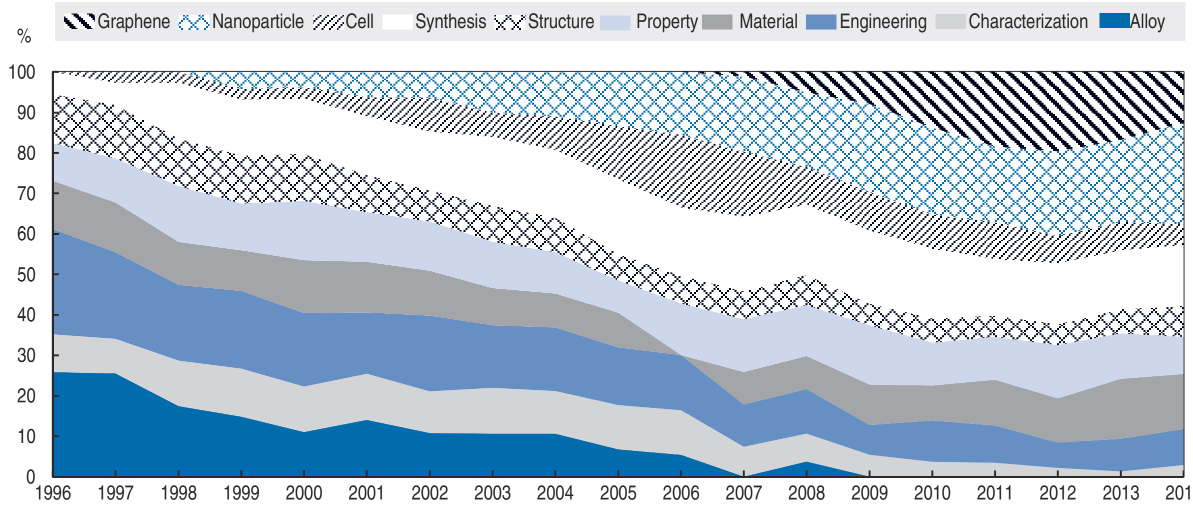
The first prediction of the innovation potential of nanotechnology is often attributed to the physicist Richard Feynman, who, in a 1959 lecture "There's plenty of room at the bottom", delivered a vision of the power to revolutionise all material sciences and technologies that would come from controlling matter on the nanometre scale (Feynman, 1960). But it was not until the development of advanced microscopy in the 1980s, and above all the invention in 1981 of the Scanning Tunnelling Microscope (STM) (which enabled real-time visualisation of the nanoscale) (Binning and Rohrer, 1986), that the term nanotechnology was coined. From then on the term was used increasingly to describe a rapidly growing interdisciplinary research area.

Research at the nanometre scale, however, is subject to thematic shifts, driven by new understanding of the nanoscale as well as other scientific breakthroughs, such as the isolation and characterisation of graphene in 2004 (Novoselov, 2004).

Figure 4.3 illustrates the changes of the ten most often appearing keywords in titles of papers in nanotechnology scientific journals between 1996 and 2014. The figure shows that over the last 20 years the main focus of nanotechnology research has shifted from being a predominantly engineering-oriented discipline concerned with inorganic materials and their properties in 1996 to a more widely applied scientific discipline. In 2014, the field of nanotechnology was predominantly concerned with specific applied materials, such as nanoparticles and graphene, and the application of nanotechnology included biological tissue, such as the cell. The percentages displayed in Figure 4.3, are based on standardised counts of occurrences of the ten most often used keywords in the titles of scientific papers, published in nanotechnology journals.

Figure 4.3. **Changing citation of the most important keywords in nanoscience literature (1996-2014)**

Share of the ten most important nanotechnology keywords in scientific literature



*Source:* Elsevier (2016), *Scopus Custom Data*, database, Version 12.2015 (accessed October 2016). Text mining performed with VOSviewer, version 6.1.3.

StatLink http://dx.doi.org/10.1787/888933473842

As the enabling aspect of nanotechnology develops further, the technology will enter a widening range of uses and require complementary technologies and institutions, such as those that foster interdisciplinary research and those that provide access to the powerful characterisation equipment needed for nanotechnology research.

Until now, however, developing an understanding of nanoscale phenomena and applying this understanding in advanced materials design and nanoscale engineering processes have proceeded much more slowly than was expected in the 1980s. The main causes for the disappointing pace of progress have been the high cost of R&D instrumentation, as well as nanotechnology's notorious failure at the stage where laboratory-scale procedures need to be scaled up and commercialised. The main hurdle to achieving commercial-scale production has been insufficient understanding of physical and chemical processes at the nanometre scale, and the inability to control production parameters at that scale. However, in recent years progress has been made in solving this problem, especially because advanced data storage and processing techniques are increasingly used in material design and development processes.

Whereas expectations of numerous new nanotechnology-enabled products were initially unfulfilled, nanotechnology-enabled innovations have gradually improved established production, manufacturing, maintenance and transport processes. Over the last ten years, R&D on, and adoption of, nanotechnology-based processes and products has increased rapidly. For example, many large companies adopted nanotechnologies as enablers to process innovations in order to reach environmental and sustainability goals (e.g. cutting carbon emissions through the lowering of reaction times in chemical production processes; increasing the fuel efficiency of their vehicle fleets by adding combustion-enhancing nanoparticles to diesel fuel; reducing the use of organic solvents by working with nanoparticles that can be suspended in water; and replacing known toxins and carcinogens in high-performance composites, such as the replacement of nickel powder in alloys for turbine blades).

The application of nanotechnology in large-scale product innovation manifested itself not as a disruptive technology, but as a step-wise improvement of known materials. An example of this is in the cosmetics sector, where large particles of zinc oxide were used in cosmetic sun-blockers, giving the cream a thick, opaque consistency. Nanotechnology was employed for the high-accuracy manufacture of only those nanometre-sized zinc oxide particles that show the highest absorption of (and thus protection against) ultraviolet (UV) light. This ultimately enabled the addition of translucent sun-block UV protection into everyday cosmetics. With regard to other applications, a 2014 report found that nanotechnology could contribute to sustainability and resource efficiency in the tyre industry, for example (OECD, 2014).

In addition, advanced nanomaterials are increasingly used in large-scale manufacturing processes for high-tech products. An example is the use of nanomaterials (mainly colloidal synthetic amorphous silica) for finely abrading and polishing electronic and optical components.

According to a study by the European Commission (EC, 2012), an estimated 70% of product innovation is based on materials with new or improved properties. Future production and manufacturing of materials and components will be increasingly digitally controlled, with sensor-based links between the so-called "digital twins" (i.e. the all-virtual design of complex objects, which runs parallel to their development in the material world, see Chapter 6) and the material world driving feedback and improvement loops based on machine learning, as discussed in the following section.

## The link between the digital and the material worlds

One of the most important medium and long-term uses of nanotechnology is in developing high-accuracy sensors and detectors. Based on the ability to probe individual atomic and molecular material building blocks, nanotechnology-enabled sensors can be made with a variety of purposes. For example, such sensors can be tailor-made to: detect organic molecules in ambient air with high sensitivity and selectivity (as is required in air safety monitoring systems); provide the results of rapid screening tests (such as those required in blood analyses during influenza epidemics); conduct online quality control during high-throughput manufacturing processes in complex systems (such as those required to produce computer chips); and, test the structure and selected properties of newly designed and developed materials (such as those created during the novel high-throughput process of concurrent design described in Chapter 6).

The role of nanotechnology as the link between the digital and physical worlds will become increasingly important, as the use of digital twins becomes increasingly widespread. For small and medium-sized enterprises (SMEs) to adopt the use of digital twins, however, the cost of this technique must be significantly decreased. The concept of "mirror worlds", created by the computer scientist David Gelernter over two decades ago, has most recently been enabled by faster Internet connections, data storage, cloud computing and advanced algorithms, which allow big data on a material's or a component's performance to be stored in huge "data lakes", ready to be used in subsequent design, development or maintenance processes (The Economist, 2016). The McKinsey Global Institute estimates that linking the physical and the digital worlds could create up to USD 11 trillion in economic value annually by 2025, with one-third of that value being created in manufacturing (McKinsey Global Institute, 2015).

Large materials and engineering companies are increasingly utilising the versatile sensor capabilities of nanotechnology to create digital twins of every category of physical asset they develop (The Economist, 2016).

## Nanotechnology's driving role in the next production revolution

Today, nanotechnology provides innovative solutions to a number of major challenges ranging from the environmental sustainability of industrial processes (e.g. through reduction of the use of energy and solvents) to the mitigation of climate change (e.g. through nanotechnology-based carbon-capture and energy-storage materials) to the affordable provision of products with preventative health benefits (e.g. through the creation of invisible sun-blockers) to the development of rapid diagnosis kits (e.g. through small-scale sensors for lab-on-a-chip applications). Three industrial cases are presented here – in solar cells, the automotive industry and plastic bottle making – to highlight the effects that nanotechnology is having, and could have, on industrial processes and technologies, with a focus on productivity.

### *Case study A: Solar cells will become safer and more widespread through nanotechnology*

Nanotechnology is set to revolutionise the nature and manufacture of solar cells in four ways:

1. Through careful design of the composition and/or the structure of a material on the nanometre scale, new photoactive materials have been created that outperform incumbent materials in at least three ways:
   - **Production cost.** The production cost of common solar cells can be significantly decreased by replacing expensive metals (such as platinum) with cheap nanocomposite materials (such as combinations of zinc oxide nanowires on flexible sheets of graphite) (MIT, 2012), or honeycomb-like structures of graphene interspaced with lithium carbonate (Michigan Technological University, 2013).
   - **Environmental safety.** The environmental safety of solar cells can be improved by replacing known toxic materials (such as lead and cadmium) with nanocomposites of little or no safety concern (Los Alamos National Laboratory, 2013).
   - **Energy efficiency.** The energy efficiency of common solar cells can be increased by reducing the thickness of photoactive material layers in solar cells to the bare minimum (i.e. to a double layer single-molecule thick sheet of graphene and other materials), thus allowing the stacking of several such cells in a single element (MIT, 2013).
2. Reducing the size of photoactive materials to the nanometre scale significantly broadened the range of industrial processes suitable for the production of solar cells, ultimately enabling the manufacturing of solar cells to shift from an energy-intensive highly specialised zone-melting process (for traditional silicon solar cells) to low-cost large-scale thin-film deposition techniques (from liquid and/or gas) and high-throughput printing techniques (e.g. screen-printing, roll-to-roll printing). The latter techniques are applied in the production of novel, so-called second- and third-generation, solar cells.
3. Thin-film solar cells furthermore enable the creation of flexible and/or spherical solar cells. This enhances collection efficiency compared to flat cells (Lin et al., 2014). Engineers at the National Renewable Energy Laboratory (NREL) in Golden, Colorado, have developed thin-film solar panels, manufactured at relatively low cost, which are flexible to the point of being able to be draped.
4. Shrinking all active components of a solar cell (i.e. the photoactive material and both electrodes) to the nanometre scale also allows the unobtrusive incorporation of near-transparent solar cells into a wide range of building components. This could enhance overall power generation from currently unused sunlight.

While the rapid advancement of solar cell technologies and the boom in the solar cell market have so far only been marginally related to nanotechnology, the technology's four-fold impact on the production of solar cells will have effects in the medium and long-term future.

At the moment, the most widely used solar cells are so-called first-generation solar cells (made of crystalline silicon) and second-generation solar cells (made of thin films of metals, which are often toxic). In the medium term, third-generation solar cells made of organic dyes will increasingly enter the solar cell market. Nanotechnology-based innovations enable both the functionality of these cells and their low-cost production process. In addition, second-generation solar cells will be improved by nanotechnology through replacement of their toxic components with nanocomposites of similar performance but fewer or no safety concerns.

In the long term, nanotechnology-enabled translucent solar cell technology and advanced printing processes will allow building components to be covered with low-cost solar cells. This could significantly increase the share of global energy consumption coming from solar, which currently stands at 1% (IEA, 2014).

### *Case study B: The automotive industry and its consumers benefit from nanotechnology-enhanced products and processes*

The automotive and transport industries greatly benefit from nanotechnology owing to these industries' rapid innovation cycles. Numerous applications have been successfully commercialised. For example, fuel efficiency and environmental performance have been improved by advanced nanomaterial-based catalysts and fuel additives; carbon black nanomaterials are enhancing the performance of tyres; and car bodies have been enriched with nanotechnology-based anti-corrosion protection.

Nanotechnology-based innovations are also revolutionising complex automotive manufacturing processes. For example, to increase the fuel efficiency and corrosion resistance of vehicles, a growing number of metal-based automotive body panels have been replaced with polymer composites. This improvement, however, has come at a cost to manufacturers and the environment, because the polymers are not electrically conductive. This meant having to exclude the new body parts from the electrostatic paint line hitherto used in production. Vehicle manufacturers now had to coat the polymer-based body parts with a conductive primer in a separate step, before the part could be painted together with the metallic parts (or manufacturers had to establish a second paint line for the polymer-based parts, often resulting in different properties and optical appearance). A solution to this problem is introduced by nanotechnology: the addition of small amounts of carbon nanofibres (i.e. extremely long, thin and light fibres consisting of carbon) to the polymer composite renders the latter electrically conductive, while no other relevant properties are affected (Burton, 2006). It was estimated that this innovation could reduce manufacturing costs by USD 100 per vehicle, with a net value to the automotive industry globally in the order of USD 2 billion annually (Burton, 2006).

### *Case study C: Nanomaterials radically reduce the cost and $CO_2$ footprint of polyethylene terephthalate (PET) bottle production*

The food processing industry is notoriously shy to adopt drastically new technologies and materials, given the heavy regulatory burden surrounding innovations in food, feed and food contact materials, as well as the increasingly sceptical and nostalgic attitudes of consumers, which affect opinions on food and nutrition more than any other consumer product. Nevertheless, it was the food processing industry that experienced one of the first and most rapid nanotechnology-based process innovations. In 2007, a patent was filed to protect the idea of including heat-absorbing nanoparticles into the freshly soft-blown plastic polymer drink bottle, in order to shorten the time necessary to harden the bottle under infrared light. In this process, titanium nitride nanoparticles act as absorbers of infrared light, thus becoming local miniature heat sources within the polymer (US DOE, 2011; Guler et al., 2013). Less than 12 months later, the European Food Safety Authority (EFSA) had reviewed and approved the safety of these nanoparticles in typical plastic drink bottles, which are made of the plastic PET (EFSA, 2008). This innovation is today sold all over the world as a concentrated solution of the nanoparticles that simply needs to be added to the PET melt at the preform injection stage. The innovation is used by some of the largest PET bottling companies.

The productivity enhancement achieved by this innovation is claimed to significantly lower manufacturing costs. The cost reduction comes from a shortening of the curing time of the hot-blown PET bottle, as well as a 38% reduction of energy use during the process, which can be translated to almost double the cost savings and twice the $CO_2$ reduction associated with any alternative polymer additive.

## Implications for public policy

### *High R&D costs may be offset by virtual infrastructures*

Significant investment is needed in R&D. Such investment can help to build research communities and to generate sufficient knowledge until the technology has matured and can support itself through industrial applications and commercialisation. Nanotechnology research is capital intensive, requiring clean-room facilities and advanced microscopy techniques during most steps of the R&D procedure. The R&D cost of nanotechnology will remain very high (for example, in the United Kingdom the use of a state-of-the-art microscope for one day might cost over GBP 5 000) and might even rise with advancing specialisation: increasingly specialised and powerful equipment, such as combined nano-fabrication (manipulation) and characterisation (imaging) devices must be used to fully understand processes and properties on the nanometre scale.

The entirety of research and engineering tools required to set up an all-encompassing R&D infrastructure for nanotechnology might be prohibitively expensive. State-of-the-art equipment costs several million euros and often requires the construction of bespoke buildings. Moreover, some of the most powerful research instruments exist as prototypes only. It is therefore almost impossible to gather an all-encompassing nanotechnology infrastructure within a single institute or even within one region. Consequently, nanotechnology requires increased efforts in inter-institutional and/or international collaboration to advance to its full potential. Publicly funded R&D programmes should allow the involvement of academia and industry (i.e. both large and small companies) from other countries. Doing this enables targeted solution-driven collaborations between the most suited partners and creates a virtual R&D infrastructure (i.e. a network of institutes and laboratories that possess complementary instruments and expertise, between which researchers can move as if they were working in a single research facility). An example of such an R&D infrastructure is the European Commission's QualityNano project (QualityNano, 2015).

The creation of virtual infrastructures that connect existing elements of R&D infrastructure in interdisciplinary networks of scientists and engineers offers a cost-saving alternative to financing multiple nanotechnology R&D centres. In addition, long-distance remote access to high-tech R&D equipment is being enabled by increasing digitalisation, such that users of state-of-the-art microscopes can even conduct their experiments from a computer terminal located on another continent.

### *Interdisciplinarity must be supported and encouraged*

Nanotechnology tends to thrive at the interface of traditional disciplines. This is where discipline-specific research and engineering infrastructures are available – favouring multidisciplinarity – and the expert knowledge in traditional disciplines is pooled. Examples of such conducive environments include virtual networks, such as Germany has created to support biomedical nanotechnology (Malsch, 2005), and research institutes such as the United Kingdom's Interdisciplinary Research Collaborations. Policy makers should seek to support multidisciplinary networks, ideally providing an R&D infrastructure. Such networks should include academia and large and small companies. Public-private-partnerships should be encouraged to foster both scientific excellence and business skills.

As a general-purpose technology (GPT), nanotechnology has an impact on a wide range of industry sectors. Policy instruments that optimally foster nanotechnology therefore need to be designed in a way that takes into account the multidisciplinary approaches that the technology can require. In 2008, most OECD countries had specific policies and dedicated R&D funding instruments in place, and approximately half of those countries had established new organisational and institutional frameworks to support nanotechnology (OECD, 2008).[1]

### *New business and innovation-funding models are required to enable the next production revolution*

The relatively high cost of nanotechnology R&D hampers the involvement and success of small companies in nanotechnology innovation. As a result, nanotechnology R&D is mainly conducted by larger companies. Large companies are better placed to assimilate nanotechnology due to their critical mass in R&D and production, their ability to acquire and operate expensive instrumentation, and their ability to access and use external knowledge (OECD, 2010). Policy makers should foster innovation and commercialisation in small companies, by providing sufficient and appropriate incentives and support for these companies to fulfil their innovation potential. Policy makers could seek to improve SMEs' access to equipment by: increasing the amount of money SMEs receive in research grants; subsidising/waiving the service fee; or providing SMEs with vouchers for equipment use. The development of networks that involve academia, public research laboratories and large and small companies creates an environment in which a research infrastructure can be shared, while simultaneously helping start-ups to establish themselves within a current or potential commercial value chain.

For future high-throughput R&D processes (such as concurrent design and digital twins described in Chapter 6) to become widely used in the nanotechnology community, decision makers in the public and private sector should consider reviewing existing business and funding models. New models may be required, because both the R&D for new and converging technologies, as well as the invention and manufacture of products enabled by these technologies, differ from traditionally observed processes (e.g. car manufacturing, food processing and steel production). Specific challenges in arriving at an adequate ecosystem may arise from the following issues:

- The ubiquitous use of concurrent design and digital twins requires the establishment of and open access to large databases that store basic R&D data (and metadata) from academic research laboratories, large industry R&D and SMEs (typically start-up and spin-out companies). A first challenge arises from questions of how the establishment of such databases should be funded, who should be responsible for the creation and maintenance of such databases, and how quality control should be governed. While it seems most appropriate that these responsibilities should fall to an international collaboration among public authorities, it is still unclear how development, maintenance and quality control costs should be covered. Public authorities should collaborate on the development of a strategy and roadmap for an internationally shared data commons.
- Policy makers also need to find a model under which pre-competitive data can be openly shared without compromising the ability of universities and small businesses to raise income. In situations where large firms, SMEs and academia were to make their basic R&D data (i.e. both product and process parameters and specifications) available in an openly accessible database (i.e. a data commons), it would be difficult (perhaps impossible) to draw up licensing deals or use agreements to benefit the upstream knowledge contributors (i.e. the scientific researchers). This lack of protection of data on basic R&D would undermine current models of collaboration between universities and industries,

such as the funding of doctorate programmes on specific research topics, which are based on the assigned ownership of different parts of the knowledge needed in the collaboration (e.g. background intellectual property [IP], peer-reviewed papers and materials metadata). Public-private collaboration agreements of this kind are typically negotiated and secured under collaboration contracts in which each party's research capacity, skills and background IP are assets that determine the party's share of ownership of the resulting invention. If a university's main bargaining asset (consisting of data on basic R&D) were to be made freely available, academia may miss out on funding from industry collaborations, and subsequently be set back by not being able to afford the purchase of state-of-the-art-equipment needed for nanotechnology R&D.

- Decision makers and policy makers should work on the creation of an innovation ecosystem that allows the pre-competitive sharing of basic R&D data without compromising the protection of IP created by those that cannot currently afford patent protection. Adequate ecosystems may be based on making patenting more affordable for SMEs, but they may also entail the protection of IP by other means.
- The concept of the digital twin increasingly emphasises the importance of computational algorithms that can turn large amounts of materials data and process data into models and simulations of inventions. If the digital twin was to become a dominant innovation tool in a value chain, value-added would shift from the R&D expert to the computing and machine-learning power of the algorithm. For example, in the value chain of turbine blade material manufacturing, the most important knowledge is currently held by materials and processing experts. These experts suggest incremental innovations to the existing materials mixture and/or the processes used to make the turbine materials and the turbine blade. In a world of digital twins, the innovative turbine blade would be developed using a digital model of itself, by continuously feeding basic R&D data on turbine blades into a machine-learning algorithm, which simulates the ideal materials components and processing parameters of a turbine blade, while continuously measuring the targeted parameters of a prototype turbine blade, and adjusting parameter settings in case of deviations. In this futuristic scenario, the computer algorithm would provide the most important innovative step. In this connection consideration should be given to the international harmonisation of IP protection for computer programmes and software, which are currently treated differently under US and EU law.

### *Regulatory uncertainties must be eliminated in internationally collaborative approaches*

Regulatory uncertainties regarding risk assessment and approval of nanotechnology-enabled products severely hamper the commercialisation of nano-technological innovation. This is because products awaiting market entry are sometimes shelved for years before a regulatory decision is made. In some cases, this has caused the closure of promising nanotechnology start-ups, while large companies have terminated R&D projects and innovative products. A 2016 OECD report investigated the treatment of some nanotechnology-enabled products in the waste stream, concluding that more needs to be done to safely integrate nanotechnology in its diverse uses (OECD, 2016a). Policies should support the development of transparent and timely guidelines for assessing the risk of nanotechnology-enabled products, while also striving for international harmonisation. Since 2006, the OECD has led international efforts to harmonise regulatory approaches to the safety of nanotechnology-enabled products (OECD, 2011).

## Note

1. An ongoing OECD study aims to find out if such early specific funding programmes for nanotechnology R&D have since been replaced by more generic policies.

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