of Possible Legislation to
Increase Transparency on
Nanomaterials on the Market

Building Blocks Report – 2<sup>nd</sup> Draft prepared for

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# Study to Assess the Impact of Possible Legislation to Increase Transparency on Nanomaterials on the Market

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**Building Blocks Report – Second Draft** 

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#### **List of Abbreviations**

**Anses** Agence nationale de sécurité sanitaire de l'alimentation, de l'environnement et du travail

ANSM Agence Nationale de Sécurité du Médicament et des Produits de Santé

CPNP Cosmetics Products Notification Portal

**EC** European Commission

**ECHA** European Chemicals Agency

**EFTA** European Free Trade Association

**EU** European Union

**FNS** French Notification System

**Ineris** Institut National de l'Environnement Industriel et des Risques

INRS Institut national de recherche et de sécurité pour la prévention des accidents du travail et des

maladies professionnelles

**InVS** Institut de Veille Sanitaire

MEDDE Ministère de l'Écologie, du Développement durable et de l'Énergie

**nm** Nanometre

NM Nanomaterial, as defined by the French authorities, unless otherwise stated

**SCCS** Scientific Committee on Consumer Safety

**R&D** Research and Development

**VAT** Value Added Tax

**XAN** The XAN number is the name approved by a specific country (X) for a cosmetics product

## 1 Introduction

#### 1.1 Overview

The overall aim of this study is to provide support to the European Commission in the preparation of an impact assessment to identify and develop the most adequate way to increase transparency and ensure regulatory oversight for nanomaterials. The contractor is expected to:

- Gather relevant information on the experience from other nanomaterials register-like schemes;
- Provide information on health and safety, markets and research trends of nanomaterials for the better definition of the policy options to be assessed; and
- Support the impact assessment of the policy options.

The technical specifications set out a detailed framework for the study and identified five different tasks, namely:

- Task 1: Lessons learned from other schemes;
- Task 2: Background information for building blocks of policy options;
- Task 3: Organise and carry out public consultations;
- Task 4: Support for the option assessment; and
- Rask 5: Validation workshop.

This Building blocks report documents the findings of Task 2 and should complement the information provided in the Evaluation report (based on the findings of Task 1) through the assessment of the French Notification System and the Cosmetic Products Notification Portal.

# 1.2 Task Objectives

Main objective of Task 2 will be the gathering of information to support the Commission in defining the optimal policy options.

The task has been divided into the following subtasks:

- Profiling risks and hazards with a view to assessing potential risks (Task 2.1);
- Characterisation of the value chain (Task 2.2);
- Overview on growth and innovation (Task 2.3);
- Setting up of a system of indicators for the monitoring of the transparency measures (Task 2.4).

# 1.3 Structure of the Building Blocks Report

The remainder of this report has been organised as follows:

- Section 2 provides an overview on the known hazards and risks of nanomaterials and the surrounding uncertainties;
- Section 3 will describe distinctive nanomaterials value chains, paying specific attention to distribution across the supply chains and sizes of the actors, margin and profits and direct and indirect employment generated by the nanotechnology sector; and
- Section 4 provides an overview on growth and innovation.



# 2 Profiling Risks and Hazards with a View to Assessing Potential Risks

#### 2.1 Introduction

The reason why manufactured nanomaterials are of such interest and offer such potentially significant benefits to society is that they often have very different properties to the same substances on the macro scale – they may be more reactive, have increased strength, etc. However, these same differences also mean that they may also be more readily absorbed into biological systems and that their hazards may be different from those of their larger forms. Nevertheless, as stated by Scientific Committee on Emerging and Newly Identified Health Risks (SCENIHR): "the hypothesis that smaller means more reactive, and thus more toxic, cannot be substantiated by the published data."

"From a toxicological point of view nanomaterials of poor solubility in biological fluids are of special importance, because they maintain their nanostructure after contact with the human body. Nanomaterials that are enclosed in an insoluble matrix are of minor importance, but may become relevant as soon as they are released by e.g. mechanical forces". It should be noted that "most of currently relevant nanomaterials occur in a solid aggregate state and have a (very) low solubility". <sup>2</sup>

Although the potential effects of nanomaterials on human health can vary from those of the chemical agents in macro-forms due to their specific physicochemical characteristics, the possible mechanisms for the generation of harm remain the same: the causation can be direct, through contact, or indirect, through the production of some form of energy which can have an adverse effect on human health. In the first case, exposure might result in an "acute effect", when the harm becomes apparent rapidly or even immediately after contact, or in a "chronic effect", when the harm appears in the long term, normally due to repeated exposure over time. Moreover, the term "local effect" is used if the harm becomes apparent at the point of contact; "systematic effect" denotes harm that appears in any point of the body regardless of the place where the contact occurred, normally following a process of absorption and distribution through the body. "The smallness of nanomaterials can lead to an increased potential to cross barriers in living organisms which increases the number of organs that can be affected" (EU-OSHA, 2009). Nanomaterials could also cause harm by fire or explosion.

Extensive research campaigns are being conducted for the understanding of the possible hazards of nanomaterials; "Not all nanomaterials are hazardous, not all nanomaterials are equally hazardous and there can be considerable variation in toxicity between nanomaterials with a similar chemical composition, because of their physicochemical characteristics".<sup>3</sup>

SCENIHR (2009): Risk Assessment of Products of Nanotechnologies, Opinion adopted at its 28<sup>th</sup> plenary on 19 January 2009. Available at: <a href="http://ec.europa.eu/health/ph-risk/committees/04-scenihr/docs/scenihr-o-023.pdf">http://ec.europa.eu/health/ph-risk/committees/04-scenihr/docs/scenihr-o-023.pdf</a>

<sup>&</sup>lt;sup>2</sup> EU-OSHA (2009): Workplace exposure to nanoparticles, European Risk Observatory Literature Review, the European Agency for Safety and Health at Work (EU-OSHA), available from the EU-OSHA Internet site: <a href="http://osha.europa.eu/en/publications/literature reviews/workplace exposure to nanoparticles">http://osha.europa.eu/en/publications/literature reviews/workplace exposure to nanoparticles</a>

HSE (2013): Using nanomaterials at work, Including carbon nanotubes (CNTs) and other biopersistent high aspect ratio nanomaterials (HARNs), Health and Safety Executive, UK.

Currently, three substances in nano-form (silicon dioxide, silver and titanium dioxide) are undergoing the Evaluation process under REACH. In addition, through the OECD's Sponsorship Programme for the Testing of Manufactured Nanomaterial, a further ten MNMs (fullerenes C60, SWCNTs, MWCNTs, iron nanoparticles, aluminium oxide, cerium oxide, zinc oxide, dendrimers, nanoclays and gold nanoparticles) are currently being evaluated and tested for approximately 59 endpoints relevant to environmental safety and human health.4

Methods for the assessment of health effects are usually divided in four groups:

- Epidemiology/occupational medicine;
- In vivo methods with animals;
- In vitro methods;
- Methods for the determination of physicochemical properties.

As reported by the Commission Staff Working Document accompanying the General Report on REACH "...further adjustment of the OECD Test Guidelines is currently being discussed by the OECD Working Party on Manufactured Nanomaterials (WPMN). Eight test guidelines have been identified as requiring adaptation. A dedicated working group within WPMN is examining the applicability of alternative testing methods to nanomaterials", with a particular care on the sample preparation and dosimetry.

Moreover, the EU has allocated €177m to a range of projects (grouped in the EU Nano Safety Cluster)<sup>6</sup> on the safety of nanomaterials through the Seventh Framework Programme (FP7). Currently there is a wide debate on the basis for Occupational Exposure Limits for generic dust. In Germany, the MAK Dust Committee has developed a proposal for limiting exposures to respirable dusts in the form of a GBS<sup>8</sup> particle limit, based on outputs from two analyses: the first by the Fraunhofer Institute, is based on low level exposure-effect relationships, while another approach developed by Pauluhn (2010 and 2011) is based on modelling alveolar/macrophase overload. This latter model is based on the effect being linked to particle density (with a focus on insoluble forms) and is particularly relevant because the dataset used includes several nano-size substances. The MAK Committee has suggested that the limit value for generic dust should be set at 1.3 mg/m3 for the respirable fraction. At the same time, they are also considering what might be necessary in the case of ultrafine dusts (which include nano-sized particles) and are currently considering the suitability of adoption of a value equal to either one tenth or one twentieth of the general dust value (pers. comm.).

OECD (2012): Important Issues on Risk Assessment of Manufactured Nanomaterials, the Organisation for and Development (OECD), OECD Economic Co-operation available from the http://search.oecd.org/officialdocuments/displaydocumentpdf/?cote=env/jm/mono%282012%298&docla nguage=en

EC (2013): Commission Staff Working Document accompanying the document General Report on REACH, Report from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions, in accordance with Article 117(4) REACH and Article 46(2) CLP. Available from http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=SWD:2013:0025:FIN:EN:PDF

http://www.nanosafetycluster.eu/

Where with "generic dust" is intended not a specific substance dust.

Granular bio-durable particles without known significant specific toxicity http://www.baua.de/en/Publications/Expert-Papers/F2083.html

In the UK the current limit values are set at 10 mg/m³ for the inhalable fraction and at 4 mg/m³ for the respirable fraction but various bodies (including the Institute of Occupational Medicine) have raised concerns regarding the extent to which these are adequate to ensure safety. Also, the WATCH scientific committee of the Health and Safety Executive (HSE) could not define a lower threshold below which there would be no lung function decline when the respiratory tract was exposed in sufficient quantities to poorly soluble dust. It is opinion of this Committee that increasing exposure results in increasing adverse health effects and, although the reviewed literature only considered kaolin, carbon black and coalmine dust, the Committee felt that "the results could probably be generalised to all other low toxicity dusts". It was suggested that setting stricter limit values (proposed at 5mg/m³ for inhalable dust and at 1 mg/m³ for respirable dust) would result pro rata in a reduction in the risk of COPD in the future. However, in December 2010 the HSE Board concluded that "only limited benefits would accrue from reducing the exposure limits for airborne dust and that it would not therefore be seeking to do this in pursuit of a long-term reduction in respiratory disease" (IOM, 2011).

At EU level, SCOEL is reviewing TiO<sub>2</sub> in the nanoform but as yet no proposal has been agreed or circulated for comments (pers. comm.). Moreover, ECETOX is working on particles overload and trying to define NOAELs that could be used to inform assessments to inform REACH, while the European Commission Joint Research Centre (JRC) is working on the feasibility of identifying generic occupational exposure limits for nanomaterials.

One of the main problems for the establishment of occupational exposure limits for nanomaterials is that, usually, OELs are based on a mass concentration metric "but the most optimal dose metrics is still undefined for nanoparticles". Fibre-like substances for which the dose-response relationship is expressed as the 'number of fibres per volume' are an exception (e.g. asbestos). There is growing evidence that a mass-based approach is not the most appropriate for nanomaterials and that a number-based approach or a particle's surface area based approach fit better the observed effects, though the recent work of Pauluhn (2010 and 2011) has suggested that a volume-based cumulative lung exposure dose metric may be most appropriate as a basis for a generic limit. Currently, however, with regard to risk assessment of nanomaterials (or ultrafine particles) a number-based approach has considerable support. Furthermore, the detection limits for number-concentration measuring devices are generally much lower than those for devices used to measure the mass exposure.

For a few specific nanomaterials, industry and research have suggested either specific OELs/RELs or DNELs (these are summarised in Table 2-1).

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<sup>&</sup>lt;sup>9</sup> IOM (2011): The IOM's position on occupational exposure limits for dust, 5th of May 2011.

<sup>&</sup>lt;sup>10</sup> Hansen and Baun (2012): European Regulation affecting nanomaterials – Review of limitations and future recommendations, Dose-Response, 10:364-383, 2012.

Wittmaack (2007a): In search of the most relevant parameter for quantifying lung inflammatory response to nanoparticle exposure: Particle number, surface area or what?, Environ Health Perspect 115:187-194, or Wittmaack (2007b): Dose and Response Metric in Nanotoxicology: Wittmaack responds to Oberdoerster et al and Stoeger et al, Environ Health Perspect 115(6): A290-291.

Pauluhn (2011): Poorly soluble particulates: Searching for a unifying denominator of nanoparticles and fine particles for DNEL estimation, Toxicology 279 (2011) 176-188, and Pauluhn (2010): Multi-walled carbon nanotubes (Baytubes®): Approach for derivation of occupational exposure limit, Regulatory Toxicology and Pharmacology 57 (2010) 78-79.

DNELs were calculated in an experimental study by Aschberger *et al*  $(2011)^{13}$  applying the DNEL methodology with the prescribed assessment factors to MWCNTs, fullerenes, Ag and TiO<sub>2</sub>.

Table 2-1: Suggested OELs and DNELs at March 2013					
Substance	Parameter	OEL or REL μg/m <sup>3</sup>	DNEL μg/m <sup>3</sup>	Reference	
MWCNT (Baytubes)	8-hr TWA	50		Pauluhn, 2010	
MWCNT (Nanocyl)	8-hr TWA	2.5		Nanocyl 2009 14	
CNT and CNF	8-hr TWA	1		NIOSH 2013 <sup>15</sup>	
MWCNT	Chronic inhalation		0.67-33.5	Aschberger <i>et al</i> 2011	
Fullerenes	Chronic inhalation		270	Aschberger <i>et al</i> 2011	
Ag (18-19nm)	DNEL		98	Aschberger <i>et al</i> 2011	
TiO <sub>2</sub> (10 -100nm) (REL)	10hr/day, 40hr/week	300		NIOSH 2011 <sup>16</sup>	

A threshold value for Carbon Nanotubes has also been set in Switzerland in 2011 by the Swiss National Accident Insurance Fund (SUVA) at 0.01 fibres/ml (SECO, 2012).

To overcome the current lack of reliable hazard data for individual nanoforms with which to derive OELs and DNELS, the adoption of Nano Reference Values (NRVs) has been proposed by the Ministry of Social Affairs and Employment in the Netherlands as a pragmatic basis for establishing provisional limit values. In fact, NRVs were first proposed by the British Standards and were subsequently further refined by the German *Institut für Arbeitsschutz der Deutschen Gesetzlichen Unfallversicherung* (IFA, 2009). It must be noted, however, that the NRVs are not health-based, rather they are intended to represent a warning or concern level. If they were to be found to be exceeded, the assumption is that additional exposure control measures should then be taken to ensure a lowering of exposure within the workplace. As such, they have been proposed as a means of implementing an approach based upon the precautionary principle that overcomes the uncertainties relating to the current state-of-the-art with regard to the technology and science.

Aschberger *et al* (2011): Analysis of currently available data for characterising the risk of engineered nanomaterials to the environment and human health — Lessons learned from four case studies, Environment International, Volume 37, Issue 6, August 2011, Pages 1143-1156, ISSN 0160-4120, http://dx.doi.org/10.1016/j.envint.2011.02.005. (http://www.sciencedirect.com/science/article/pii/S0160412011000365)

Nanocyl (2009): Responsible Care and Nanomaterials Case Study Nanocyl. Presentation at European Responsible Care Conference, Prague 21-23<sup>rd</sup> October 2009. http://www.cefic.be/files/downloads/04\_nanocyl.pdf

NIOSH (2013): NIOSH Current Intelligence Bulletin 65, Occupational Exposure to Carbon Nanotubes and Nanofibers, April 2013. Available online at: <a href="http://www.cdc.gov/niosh/docs/2013-145/pdfs/2013-145.pdf">http://www.cdc.gov/niosh/docs/2013-145/pdfs/2013-145.pdf</a>

NIOSH (2011): Occupational Exposure to Titanium Dioxide, Current Intelligence Bulletin 63, April 2011. http://www.cdc.gov/niosh/docs/2011-160/pdfs/2011-160.pdf

## 2.2 Concerns over Physical Hazards

There remains a lack of knowledge and a need for further research on the physical hazards associated with nanomaterials. By way of example, when handling nanopowders, particular attention should be paid to the catalytic effects and the risk of fire or explosion. INRS (2013<sup>17</sup>) note that very few nanomaterials have been specifically tested for such hazards.

Moreover, in some specific work activities, other possible hazards should be considered, for example:

- during the generation of a plasma via the use of high currents, hazard of electrocution might be increased;
- during work activities with possible leaks of inert protective gases there might be an asphyxiation hazard.

Due to their greater surface area, nanoparticles can be easily charged electrostatically, thus increasing the risk of ignition and the violence of an explosion. Furthermore, due to their size, they might remain airborne for longer time, thus increasing the possibility of creating potentially explosive dust clouds.

The Nanosafe2 project<sup>18</sup> ranked various carbon black powders, aluminium nanoparticles of different sizes and carbon nanotubes in terms of their flammability and explosivity: on a scale from 0 to 3, where 0 is "no explosion", 1 corresponds to "weak explosion", 2 to "strong explosion" and 3 to "very strong explosion", carbon black and carbon nanotubes are in the dust explosion class 1 "weak explosion", while aluminium nanopowders, depending on the particle size, were ranked in the highest classes 2 and 3, from "strong explosion" to "very strong explosion".

#### 2.3 Concerns over Health Hazards

#### 2.3.1 Overview

As is the case regarding the physical hazards posed by MNMs, there is a general lack of data on the health hazards arising from their use. However, there is generally an awareness that MNMs and nanomaterials in general do require extensive evaluation. As described in a recent EEA (2013) report, the development of nanotechnology has coincided with "...discussions of potential risks and the need for regulatory reform" unlike preceding technologies where the discussions of associated risks have generally been carried out after their widespread use. However, as the EEA (2013) report highlights, there has been a lack of coordinated action from governments and regulatory bodies.

Despite nanotechnology receiving attention of regulators and the wider public throughout its development, there is considerable concern about its use among consumers and NGOs. The

INRS (2013): Nanomaterials – Current situation and prospects in occupational health and safety, Paris, INRS, dated September 2013, <a href="http://www.inrs.fr/accueil/dms/inrs/PDF/cp-nanos-bilan-perspective-english/cp-nanos-bilan-perspective-english.pdf">http://www.inrs.fr/accueil/dms/inrs/PDF/cp-nanos-bilan-perspective-english.pdf</a>

<sup>18</sup> http://www.nanosafe.org/

EEA (2013): Late lessons from early warnings: science, precaution, innovation, EEA Report No 1/2013, available at http://www.eea.europa.eu/publications/late-lessons-2, accessed 04 March 2014

concerns of both the public and policy makers have prompted the creation of various initiatives. For example, the creation of the Project on Emerging Nanotechnologies Consumer Products Inventory. This inventory seeks to list consumer products that may contain nanomaterials. It is based on crowdsourced information regarding claims about product contents and thus relies on input from third parties to ensure its accuracy. Friends of the Earth (2011) raise concerns regarding the policies surrounding nanomaterials and their health and environmental hazards associated with nanotechnology such as the use of nano-silver antibacterial products.

#### 2.3.2 Epidemiological studies

Epidemiological studies were mainly conducted on the effects of carbon black, one of the MNMs that has been used for many decades. However, the International Agency for Research on Cancer (IARC) evaluates carbon black as *possibly carcinogenic to humans (Group 2B)*, as there is sufficient evidence in experimental animals but inadequate evidence in human epidemiological studies. <sup>21</sup> Moreover, it is not certain whether workers were exposed to carbon black at nanoscale or microscale. This same uncertainty also undermines epidemiological studies on nano-titanium dioxide. With regard to carbon black, it has to be noted that the Scientific Committee on Consumer Safety (SCCS) concluded that nano-structured form of carbon black with a particle size of 20 nm or larger can be safely use as a colorant in cosmetic products in concentration up to 10% when applied in healthy, intact skin, "based on the current available scientific evidence which shows an overall lack of dermal absorption."<sup>22</sup>

According to the Health Effects Institute<sup>23</sup>, a growing number of epidemiological studies have been conducted over the last ten – fifteen years on the human health effects of ultrafine particles (naturally-occurring nanoparticles). However, the evidence of adverse effects from short-term exposure to ambient UFPs on acute mortality and morbidity from respiratory and cardiovascular diseases is suggestive rather than conclusive. Due to underlying deficiencies in exposure data, it is not possible to conclude (or exclude) that UFPs alone account substantially for the adverse effects associated with other ambient pollutants such as PM<sub>2.5</sub>. No epidemiological studies of long-term exposures to UFPs have been conducted so far.

#### 2.3.3 Toxicity tests

Due to the uncertain reliability of in-vitro methods to assess the health effects of nanomaterials and the limited and inconclusive epidemiological evidence, in-vivo studies provide most of the data on which the current concerns have been built.

Short and mid-term duration animal studies have provided evidence of toxic effects to the lung (inflammation, cytotoxicity and tissue damage) of different types of MNMs (e.g. carbon black, titanium dioxide, carbon nanotubes, C<sub>60</sub>-fullerenes and amorphous silicon dioxide). However, there is conflicting evidence on the higher potency of nanomaterials compared to micro-sized particles.

http://www.nanotechproject.org/, accessed 03 March 14.

http://monographs.iarc.fr/ENG/Monographs/PDFs/93-carbonblack.pdf

SCCS (2013): Opinion on Carbon Black (nano-form), Opinion adopted at its 4<sup>th</sup> plenary meeting on 12 December 2013. Available at:

http://ec.europa.eu/health/scientific committees/consumer safety/docs/sccs o 144.pdf

HEI (2013): Understanding the Health Effects of Ambient Ultrafine Particles, HEI Review Panel on Ultrafine Particles, HEI Perspective 3, Health Effects Institute, Boston, Massachusetts.

Markers of inflammation in the brain were observed in rats following inhalation exposure to nanomanganese. Some preliminary studies detected effects similar to those of asbestos for specific modification of carbon nanotubes. Several types of nanomaterials have shown the capacity of systemic distribution in the organism; however, the toxicological implications of the availability of MNMs in further organs were not sufficiently classified.

Animal studies of long-term duration raised evidence on lung toxicity following inhalation exposure to nano-carbon black and nano-titanium dioxide and lung tumours were evoked in rats. The intratracheal instillation of different types of MNMs (namely carbon black, aluminium oxide, aluminium silicate, titanium dioxide, and amorphous silicon dioxide) has induced tumours and a higher potency of nanomaterials compared to micro sized particles have been observed. "However, there are insufficient data to confirm the health consequences of long-term repeated exposure" (HSE, 2013).

Landsiedel *et al* (2010) describe NOAEC or LOAEC values derived from short term inhalation trials in rats. These are expressed in terms of mg/m³ of various nanoparticles. The values reported by Landsiedel et al. are shown in Table 2-1 for the nanomaterials that have suggested OELs (see above). It is worth noting that comparisons between the results of various studies are particularly difficult for nanomaterials in comparison to macromaterials. The studies may have been carried out using different sources of nanoparticles and thus they are likely to have a different distribution of nanoparticle sizes and shapes as these are dependent on the exact production method or source. Therefore if the study does not provide an adequate characterisation of the nanomaterial composition, it may be impossible to make comparisons their toxicological profiles.

Table 2-1: Comparison of suggested OEL/DNEL values and NOAEL and LOAEC for nanomaterials					
Nanomaterial	Aerosol Concentrations tested (mg/m³)	itions OEL/DNEL* NOAEC/LOAEC Pathology Rev			
MWCNT	0.1, 0.5, 2.5	OEL/REL 0.05	NOAEC 0.1	Inflammation	No
Carbon Black	0.5, 2.5, 10	DNEL (for fullerenes) 0.27	NOAEC 10	No effects	-
TiO <sub>2</sub>	2, 10, 50	OEL/REL 0.3	LOAEC 2	Histocytosis	Not complete

Source: Landsiedel et al (2010). Note: The sources of nanoparticles are not necessarily comparable for the studies leading to the derivation OEL/DNEL and the NOEAC/LOAEC. \* OEL/DNEL reported as  $\mu$ g/m³ in Table 2-1

The US National Institute for Occupational Safety and Health (NIOSH) has determined, in light of the results of in-vivo studies, that exposure to ultrafine  $TiO_2$  should be considered a potential occupational carcinogen, acting "through a secondary genotoxicity mechanism that is not specific to  $TiO_2$  but primarily related to particle size and surface area".

Moreover, "the higher mass-based potency of ultrafine  $TiO_2$  compared to micro sized  $TiO_2$  is associated with the greater surface area of ultrafine particles for a given mass". This has led to the setting of different Recommended airborne Exposure Limits of 2.4 mg/m³ for fine (micro sized)  $TiO_2$  and 0.3 mg/m³ for ultrafine (nano sized)  $TiO_2$  (including manufactured nano- $TiO_2$ ), as time-weighted average (TWA) concentrations for up to 10 hours per day during a 40-hour work week.

Importantly, NIOSH concluded that:

the adverse effects of inhaling  $TiO_2$  may not be material-specific but appear to be due to a generic effect of poorly soluble low-toxicity (PSLT) particles in the lungs at sufficiently high exposure. While NIOSH concludes that there is insufficient evidence to classify fine

 $TiO_2$  as a potential occupational carcinogen, NIOSH is concerned about the potential carcinogenicity of ultrafine and engineered nanoscale  $TiO_2$  if workers are exposed at the current mass-based exposure limits for respirable or total mass fractions of  $TiO_2$ . NIOSH recommends controlling exposures as low as possible, below the RELs" (NIOSH, 2011).

Despite a lack of clear consensus regarding the potential health impacts of nanoparticles, numerous studies and reviews have been published. DFG (2013)<sup>24</sup> provides a recent review of the literature surrounding nanomaterial toxicology. Table 2-3 summarises some of the recent studies mentioned in this chapter alongside reports of industrial or consumer health incidents. It is important to emphasise that this is not intended to represent a comprehensive review of all literature regarding the toxicology of nanomaterials.

Table2-3: Su	mmary Table			
Substance	Studies	Study type	Weaknesses etc.	Incidents
C60	Landsiedel <i>et al</i> , 2010	In vivo inhalation and in vitro	Carbon black studied not specifically C60	
C00	Stone <i>et al</i> , 2009	Review		
	Pauluhn, 2010		Analysis of "Baytube"- type MWCNTs	
	Stone <i>et al</i> , 2009	Review		
	Nanocyl, 2009	Presentation		
MWCNT	Landsiedel <i>et al</i> , 2010	In vivo inhalation and in vitro	Short term inhalation only; 6 hours/day for five consecutive days. Single type of MWCNT. Comparable with 90-day inhalation trials	
	Ma-Hock <i>et al</i> , 2009	In vivo inhalation	Analysis of Nanocyl MWCNT using OECD 413	
CNT and CNF	NIOSH 2013	Report		
Manganoso	Elder et al 2006			
Manganese oxide	Oberdörster et al, 2009			
Gold	DFG, 2013	Review	Accumulation in tissues only, no pathology observed	
Silver	Stone <i>et al,</i> 2009	Review		
	Wijnhoven <i>et al,</i> 2009	Review		Silzone heart valve impants; Acticoat wound dressing; colloidal silver
Titanium	Landsiedel <i>et al</i> , 2010	In vivo inhalation and in vitro		
dioxide	NIOSH, 2011	In vivo inhalation and in vitro		

DFG (2013): Nanomaterials - Commission for the Investigation of Health Hazards of Chemical Compounds in the Work Area, Bonn, Deutsche Forschungsgemeinschaft, available via <a href="http://www.dfg.de/en/dfg">http://www.dfg.de/en/dfg</a> profile/statutory bodies/senate/health hazards/

Table2-3: Summary Table					
Substance	Studies	Study type	Weaknesses etc.	Incidents	
Zinc oxide	Landsiedel <i>et al,</i> 2010	In vivo inhalation and in vitro			
Silica	Landsiedel <i>et al,</i> 2010	In vivo inhalation and in vitro			
Cerium oxide	Landsiedel <i>et al,</i> 2010	In vivo inhalation and in vitro			
Polyacrylic ester paste	Song <i>et al,</i> 2009	Case study	Poor risk management measures and occupational hygiene. Limited characterisation of fumes/smoke and particles	Seven Chinese female workers developed lung damage after 5-13 months exposure to nanoparticle containing paste	

#### 2.3.4 Nanomaterials in consumer products

As should be apparent from the preceding text, much of the information concerning exposure to nanomaterials is related to occupational exposures. Of course, consumers may also be exposed to nanomaterials present in a range of products. Although there is a significant number of reports and studies on how the presence of nanomaterials could be measured, reports on actual measurements are more difficult to find. In the Netherlands, some work has been undertaken by RIVM<sup>25</sup> but, given the lack of exposure data, it is not surprising that RIVM note: *Possible health effects of consumers of using nano-products are not known.*<sup>26</sup>

#### 2.4 Concerns over Environmental Hazards

Since 206, OECD has published 40 authoritative documents<sup>27</sup> on the 'Safety of Manufactured Nanomaterials'. Throughout there has been a recognition that methods to measure and assess environmental pathways and resultant effects on the environment will be required. By inspection of the more recent publications, it is apparent that considerable knowledge gaps remain. By way of example, OECD (2012)<sup>28</sup> presents a long list of research needs to reduce the inherent uncertainties including:

RIVM (2011); Nanomaterial in consumer products: Detection, characterisation and interpretation, <a href="http://www.rivm.nl/en/Documents">http://www.rivm.nl/en/Documents</a> and <a href="publications/Scientific/Reports/2011/mei/Nanomaterial\_in\_consumer\_products">publications/Scientific/Reports/2011/mei/Nanomaterial\_in\_consumer\_products</a> Detection characterisation and interpretation

http://www.rivm.nl/en/Topics/C/Consumer exposure to chemical substances/Nanomaterials in consumer products

http://www.oecd.org/science/nanosafety/publicationsintheseriesonthesafetyofmanufactured nanomaterials.htm

OECD (2012): Important Issues on Risk Assessment of Manufactured Nanomaterials, <a href="http://search.oecd.org/officialdocuments/displaydocumentpdf/?cote=env/jm/mono%282012%298&doclanguage=en">http://search.oecd.org/officialdocuments/displaydocumentpdf/?cote=env/jm/mono%282012%298&doclanguage=en</a>

Ecological Effect Research Needs: Understanding the disposition of nanomaterials (i.e. ADME) within whole organisms in all trophic levels. This information will provide an understanding as to whether standard ecotoxicological studies are an effective indicator of toxicity for nanomaterials, as well as provide insight on mode of toxicity and species sensitivities

Persistence, Bioaccumulation, Fate and Distribution: *Identify mechanisms of* bioaccumulation, as well as developing means for predicting bioaccumulation, as well as potential for food chain transfer. Bioaccumulation and food chain transfer are crucial in conventional chemical risk assessments, however, there is no confidence that approaches employed for chemicals are applicable to nanomaterials.

In addition, there is an emerging consensus that some nanomaterials may present a risk to the environment. By way of example, in a recent study for the Swiss authorities<sup>29</sup>, it is reported that nano-titanium dioxide (as used in some sun-screens) and nanosilver (as an anti-microbial agent) are hazardous to the aquatic environment. A recent detailed review by SCENIHR<sup>30</sup> on nano-silver concludes that:

.. while in the environment Aq-[silver nanoparticles] may be a particularly effective delivery system for silver to organisms in soil, water and sediment and may act as sources of ionic silver over extended periods of time. Therefore, additional effects caused by widespread and long term use of Ag-NPs cannot be ruled out.



SCENIHR (2013): Nanosilver: safety, health and environmental effects and role in antimicrobial resistance, Preliminary Opinion, Scientific Committee on Emerging and Newly Identified Health Risks, December 2013 http://ec.europa.eu/health/scientific committees/emerging/docs/scenihr o 039.pdf

## 3 Value Chain Characterisation

#### 3.1 Introduction

This section is based on the information gathered via the online consultation and associated research.

# 3.2 French Notification System

Some preliminary data were published in the French public report (Anses, 2013) and Figure 3-1 shows the distribution of the notifiers across the supply chain.

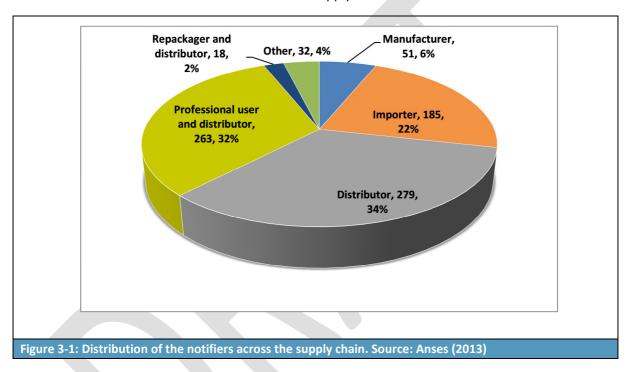


Table 3-1 presents the average number of notifications per role in the supply chain. No information has been reported on the 32 entities that indicated "other" as role in the supply chain. It must be noted that the notifiers could indicate multiple roles for each notification.

Table 3-1: Average number of notification per role in the supply chain					
Role No. of notifications Average No. of notification					
Manufacturer	149	3			
Importer	923	5			
Distributor	1,121	4			
Professional user and distributor	982	4			
Repackager and distributor	35	2			
Other	(32)	n/a			

Table 3-2 presents the number of substances per notified sectors of use.

Code	3-3: Number of substances per notified sectors of use (SU)  Main user groups		NMs		
SU 3	Industrial uses: Uses of substances as such or in preparations* at industrial				
30 3	sites		0		
SU 21	Consumer uses: Private households (= general public = consumers)		0		
SU 22	Professional uses: Public domain (administration, education,		0		
	entertainment, services, craftsmen)				
Code	Supplementary descriptor: Sectors of end-use	NACE codes	NMs		
SU1	Agriculture, forestry, fishery	Α	60		
SU2a	Mining, (without offshore industries)	В	3		
SU2b	Offshore industries	B 6	1		
SU4	Manufacture of food products	C 10,11	8		
SU5	Manufacture of textiles, leather, fur	C 13-15	7		
SU6a	Manufacture of wood and wood products	C 16	3		
SU6b	Manufacture of pulp, paper and paper products	C 17	18		
SU7	Printing and reproduction of recorded media	C 18	5		
SU8	Manufacture of bulk, large scale chemicals (including petroleum products)	C 19.2+20.1	9		
SU9	Manufacture of fine chemicals	C 20.2-20.6	27		
SU 10	Formulation [mixing] of preparations and/or re-packaging (excluding alloys)	C 20.3-20.5	132		
SU11	Manufacture of rubber products	C 22.1	24		
SU12	Manufacture of plastics products, including compounding and conversion	C 22.2	70		
SU13	Manufacture of other non-metallic mineral products, e.g. plasters, cement	C 23	10		
SU14	Manufacture of basic metals, including alloys	C 24	2		
SU15	Manufacture of fabricated metal products, except machinery and equipment	C 25	7		
SU16	Manufacture of computer, electronic and optical products, electrical equipment	C 26-27	6		
SU17	General manufacturing, e.g. machinery, equipment, vehicles, other transport equipment	C 28-30,33	21		
SU18	Manufacture of furniture	C 31	3		
SU19	Building and construction work	F	28		
SU20	Health services	Q 86	7		
SU23	Electricity, steam, gas water supply and sewage treatment	C 35-37	2		
SU24	Scientific research and development	C72	32		
SU0	Other 147				
Not rep	ported		1		
	It must be noted that the numbers do not add up as for each substance differe	ent sectors of us	se have		

Note: It must be noted that the numbers do not add up as for each substance different sectors of use have been notified

# 3.3 Survey Results

#### 3.3.1 Supply chain role

supply chain (multiple ticks and indication of primary role possible<sup>31</sup>). 25 of these manufacturers stated that being a manufacturer was their primary role in the supply chain (40%). One

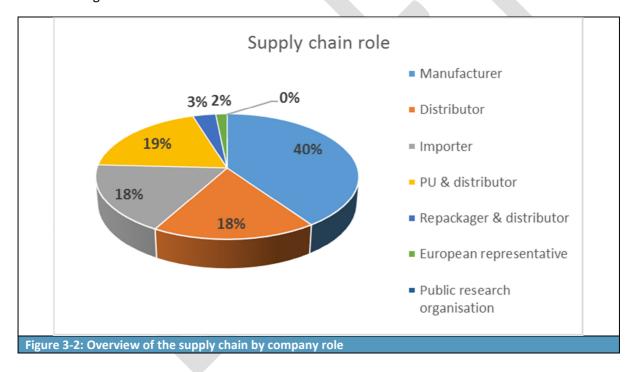
Most companies indicated they were manufacturers (26 replies) when asked for their role in the

For companies, who only selected one role, the selected role was considered as their primary role. For companies indicating more than one role, but without stating one of the roles as being their primary role, all selections were equally counted as primary role.

manufacturer stated that being a professional user and distributor was its main activity. The counts are summarised in the table below and depicted in the subsequent figure (primary role).

Table 3-4: Overview on the supply chain position of the companies					
Supply chain position	No. of companies	of which primary role			
Manufacturer	26	25			
Distributor	26	11			
Importer	26	11			
Professional user (PU) & distributor	15	12			
Repackager & distributor	4	2			
European representative	2	1			
Public research organisation	0	0			

The role of professional user and distributor (19%) achieved second place, followed by `distributors' and `importers', each with 18%. The roles of `repackager and distributor' (3%) and `European representative' (2%) play a minor role, and none of the companies identified themselves as public research organisations.



#### 3.3.2 Number of notifications

The number of notifications to the FNS for 2013 and 2014 (2014 based on estimations by the companies) were calculated (average and median) for each supply chain role, taking into account company sizes as shown in Table 3-5 (next page).

Calculation of representative average values for the number of notifications to the CPNP was not feasible because only nine companies reported notifications to the CPNP for the year 2013 (number of notifications lying between one and 10,000 notifications; average: 1119; median: 7). With

respect to supply chain position, no indications on the number of notifications to the CPNP were made, with few exceptions, so no representative values could be calculated.

Table 3-5: Number of notifications to the FNS in the year 2013 and 2014 by supply chain position and company size (no. of companies with a specific size with respect to supply chain position, years indicated with average and median value of notifications; median in brackets)

Supply chain position	No.	Micro	Small	Medium	Large
			2 companies	6 companies	16 companies
Manufacturer	25	-	2013: 11 (8)	2013: 2 (1)	2013: 832 (8)
			2014: 11 (8)	2014: 1 (1)	2014: 815 (4)
		1 company	2 companies	3 companies	5 companies
Distributor	11	2013: 2 (2)	2013: 3 (2)	2013: 5 (6)	2013: 24 (10)
		2014: 2 (2)	2014: 2 (2)	2014: 3 (3)	2014: 27 (13)
			1 company	1 company	9 companies
Importer	11	-	2013: 3 (3)	2013: 2 (2)	2013: 9 (7)
			2014: 3 (3)	2014: 2 (2)	2014: 6 (3)
			1 company	3 companies	8 companies
PU & distributor	12	-	2013: 13 (13)	2013: 10 (6)	2013: 10 (3)
			2014: 13 (13)	2014: 8 (3)	2014: 1 (0)
				1 company	1 company
Repackager & distributor	2	-	-	2013: 6 (6)	2013: 22 (22)
				2014: 3 (3)	2014: 24 (24)
				1 company	
European representative	1	-	-	2013: 6 (6)	-
				2014: 3 (3)	
Public research organisation	0	-	-	-	-

Based on the company replies and calculations made, it can be concluded that for micro sized companies, no representative values are available. From the two companies of micro size, one company made no indication with respect to the number of declarations, while the other one (being a distributor) indicated two declarations for the reporting year 2013 and another two declarations for 2014 on an estimation basis. Also, with regard to small companies, only one to two indications were made for the supply chains relevant, resulting in less representative values. For medium and large companies, it can be derived that large companies submitted a higher number of notifications than medium sized companies for the year 2013, a trend that continued for the reporting year 2014. The figure below describes the relationship between supply chain position and the number of notifications of companies with a specific size<sup>32</sup> made in 2013.<sup>33</sup>

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For the number of notifications calculated median values were used.

<sup>&</sup>lt;sup>33</sup> It should be noted that the values describing micro and small companies are not representative due to the low number of replies/indications.

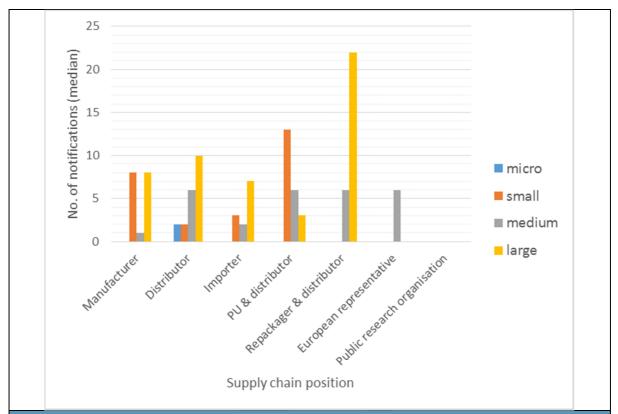


Figure 3-3: Overview on relation between supply chain positions and the number of notifications of companies with respect to company size

Further, it can be summarised that medium sized companies are distributed along the whole supply chain, similar to large companies. The following graph describes the relationship between supply chain position and number of companies with a specific size.

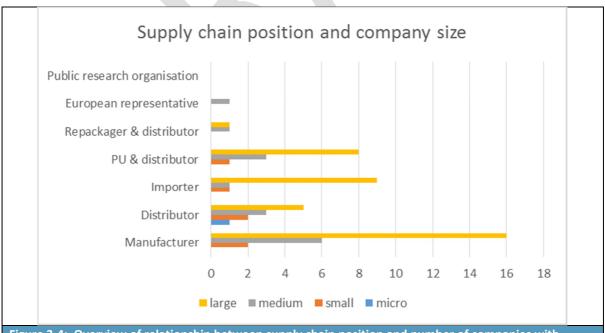
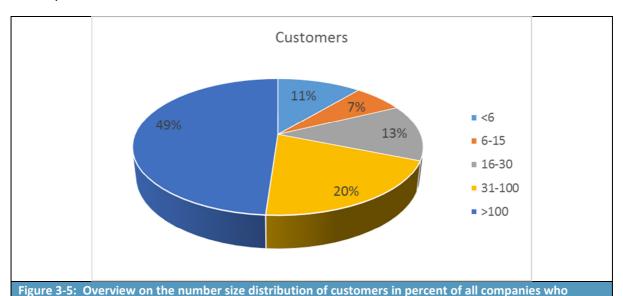


Figure 3-4: Overview of relationship between supply chain position and number of companies with respect to company size

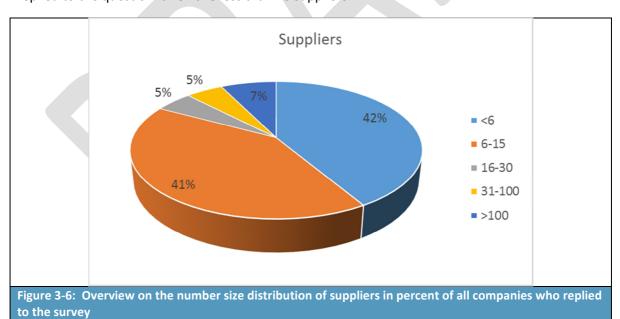
#### 3.3.3 Information on customers and suppliers

replied to the survey

Analysing the company responses relating to the number of suppliers and customers, it can be stated that nearly half of the companies (49%) have more than 100 customers (see Figure 3-5 below).



With respect to suppliers, it can be concluded that in general more than 80% of the companies who replied to the questionnaire have less than 16 suppliers.



Considering the companies' size and the supply chain position, it can be summarised that for large companies the majority has more than 100 clients (64%) all along the different supply chain positions reported and a small number of suppliers (77% with less than 16 suppliers). For medium sized companies, either no specific trend can be identified or the number of replies does not allow a reliable evaluation. In contrast, 78% of the medium sized companies responded that they had less

than six suppliers. Again, for micro sized and small companies, no representative values could be calculated owing to the low number of replies.

# 3.3.4 Overview on the distribution of nano-related products on different markets

Companies were asked to indicate the number of their nano-related products<sup>34</sup> with respect to the type of product (pure substance, in a mixture or article according to the scope of the FNS) as well as the markets on which these products are placed (French market, EU market and global market). Based on the replies received, it is very difficult to make a conclusion with respect to the different supply chain actors.

Basically, it can be summarised that more than half of the companies place less than six products on the market (53%), while around 15% of the companies indicated they place between 11 and 50 products and 12% more than 1000 nano-products on the French, EU and/or global market.

Ca. 40% of the products are placed on the French market, about 33% on the EU market and around 28% are placed on the market worldwide. These products mostly relate to the nano-substance in pure form and contained in mixtures.

<sup>&</sup>lt;sup>34</sup> where these include substances in nanoform as well as mixtures and articles containing nanomaterials

#### 4 Overview on Growth and Innovation

#### 4.1 Proxies for Innovation

Innovation is typically measured via imperfect proxies owing to the inherent difficulty of measuring it directly. Such proxies include:

- R&D spending
- Number of people employed in R&D
- Patent applications and approvals
- Journal papers published

While each of these relates to innovation in obvious ways, they all come with limitations. Small companies may not, for example, need to conduct a lot of R&D, as measured by R&D spending and the number of people employed in R&D, to generate innovation because of international flows of capital and ideas (Crosby, 2000). If such countries cannot access the economies of scale associated with the production of innovation, it may be more cost effective to borrow foreign R&D through either the purchase of new goods and processes or the purchase of patent rights.

Crucially, R&D is an input to innovation outputs rather than a measure of innovation occurring in an economy. The relationships between R&D and innovation outputs are likely to vary with time and occur with uncertain lags, and they may be non-linear.

There are similar problems with the relationships between patents and innovation outputs, but patents are at least likely to be more closely related to those outputs. Both R&D and patents measure innovation with error: a certain proportion of R&D and patents will have no impact on technological growth, productivity or GDP. For this reason, it is important that they be viewed together when drawing conclusions about innovation.

As a proxy for innovation, patents are limited in other ways. For example, a patent application may be submitted under the name of a subsidiary, rather than the parent company. Also, it is perfectly possible for the research to be conducted in one region and the corresponding patent application to be submitted in another.

In addition, a significant proportion of technological innovations in manufacturing do not result in patent applications, however this should not affect the usefulness of patent data for measuring trends as long as the average propensity to patent does not change over the period under investigation.

Proxy data are discussed here and the limitations of such data, as outlined, should be noted.

# 4.2 R&D Spending

#### **4.2.1** Public

Data relating to public spending on nanomaterial R&D is available, but using it not completely straightforward for two reasons.

First, the science of nanomaterials is not frequently separated from the broader field of nanotechnology. Research on the manufacture of molecular machines from DNA, for example, would invariably be considered nanotechnology without pertaining to bulk nanomaterials.

Second, because of the highly interdisciplinary nature of the activity, not all nanotechnology R&D is labelled as such. There are some extremely high value national and international R&D programmes currently funding projects that focus exclusively on nanotechnology. The US National Nanotechnology Initiative is typical of these. But operating in the shadows is a host of individual projects that involve nanotechnology without explicitly saying so.

That said, the science of nanomaterials is a very significant part of nanotechnology. Additionally, it is probably the field of nanotechnology most likely to appear beneath a nanotechnology banner. Most other fields stand a higher – if still relatively small – likelihood of appearing beneath another banner. Pharmaceutical nanotechnology might, for example, be labelled healthcare for the purposes of public funding.

Here then, we have reviewed nanotechnology in general where – as is frequently the case – the degree of demarcation in the relevant reference sources is insufficient to facilitate a meaningful discussion of nanomaterials in isolation.

#### EU

In general, EU spending on nanotechnology R&D has increased over the last 10–15 years, although successive funding programmes have organised work in different ways making direct comparisons difficult.

Under the Sixth Framework Programme (FP6), the EU spent €1.3bn on nanotechnology R&D (shared between 550 projects) in the five years from 2002 to 2006. It then spent €3.5bn in the seven years from 2007 to 2013 on the 'nanosciences, nanotechnologies, materials and new production technologies' theme of the Seventh Framework Programme (FP7).

It is now spending €3.85bn on 'nanotechnologies, advanced materials and advanced manufacturing and processing' under Horizon 2020, which will run for seven years from 2014 to 2020<sup>35</sup>.

Data from Georgalis and Aifantis show that annual spending through these programmes increased steadily from 1997 to 2009 (Georgalis & Aifantis, 2013).

#### **EU** member states

The UK research councils and other public funding organisations provide money for nanotechnology R&D. Of these, the Engineering and Physical Sciences Research Council (EPSRC) most likely provides the most. At the time of writing, live EPSRC grants with the socio-economic theme nanotechnology accounted for €217m (£176m) of funding<sup>36</sup>. As grants are typically provided for periods of more than one year, this figure represents funding for several years.

According to a report from industry group Materials UK and the Knowledge Transfer Networks (KTNs), the UK government provided €790m (£640m) for nanotechnology over the 12 year period from 1998 to 2010 (Materials UK, 2010). The breakdown of this spending is shown in Table 4-1.

<sup>35</sup> http://horizon2020projects.com/industrial-leadership/nanotechnology/

<sup>36</sup> http://gow.epsrc.ac.uk/NGBOListSocioThemes.aspx

Table 4-1: Estimated UK government support for nanotechnology based on Department for Business, Innovation & Skills data			
Year	Estimated amount (millions of €/£)		
2009/2010	102 / 83.2		
2008/2009	96 / 77.6		
2007/2008	91 / 73.5		
2006/2007	82 / 66.2		
2005/2006	81 / 66.0		
2004/2005	81 / 65.8		
2003/2004	75 / 60.8		
2002/2003	50 / 40.6		
2001/2002	62 / 50.0		
2000/2001	44 / 35.5		
1999/2000	14 / 11.0		
1998/1999	15 / 12.4		

The German government directed €400m of public money into nanotechnology R&D in 2010 (Federal Ministry of Education and Research (BMBF), 2011), up from \$500m in 2008 (Materials UK, 2010), making the German government one of the biggest spenders globally.

France ran a €2.3bn national public—private nanotechnology R&D programme, Nano2012, from 2008 to 2012 (five years)<sup>38</sup>. In 2009, the French government announced it would commit €457 in public money to the programme<sup>37</sup>, which was led by STMicroelectronics, a French–Italian semiconductor company.

In 2013, the French government announced that it would be contributing to €600m to Nano2017, the follow-up to Nano12<sup>38</sup>. Like its predecessor, the programme is set to run for five years, will focus on nanotechnology and involve both public money, including €400m from the EU, and private money, including €1.3bn from some stakeholders.

According to reference sources, France spent €210m of public money on nanotechnology R&D in 2008 (Materials UK, 2010).

#### The rest of the world

The US National Nanotechnology Initiative (NNI) has supplied about €15bn (\$20bn) of public money to nanotechnology R&D since its launch in 2000<sup>39</sup>. Its annual budget grew steadily through the 2000s, but then stalled in the wake of the 2007–8 global financial crisis at about €1.4bn (\$1.9bn), as can be seen in Table 4-2. The budget fell significantly in 2013 but has since levelled out at about €1.1bn (\$1.5bn).

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http://www.electronics-eetimes.com/en/nano2012-r-d-program-is-officially-launched.html?cmp\_id=7&news\_id=218501185

http://www.nanotechia.org/news/news-articles/french-prime-minister-launches-eur-35-billion-public-private-partnership-nano

http://www.nano.gov/about-nni/what/funding

Table 4-2: NNI annual budget		
US fiscal year	Allocation (millions of €/\$)	
2015	1130 / 1540*	
2014	1130 / 1540**	
2013	1140 / 1550	
2012	1370 / 1860	
2011	1360 / 1850	
2010	1400 / 1910	
2009	1250 / 1700	
2008	1140 / 1550	
2007	1050 / 1430	
2006	992 / 1350	
2005	882 / 1200	
2004	727 / 989	
2003	559 / 760	
2002	512 / 697	
2001	341 / 464	
*Proposed; **estimated		

The NNI budget represents only part of the public money available for nanotechnology R&D in the US. It does not included, for example, money from state initiatives. In the 2011 fiscal year, the NNI spent €1.36bn (\$1.85bn), but Cientifica, a market research firm, estimated total government spending at \$2.18bn<sup>40</sup>.

The Russian strategy towards funding of nanotechnology R&D coalesced in 2007 in the form of the Development Programme for Nanoindustry in the Russian Federation (Connolly, 2013). Through this program, the government planned to spend about €2.12bn (py6100bn) from 2008 to 2015. Specifically, it created a federal targeted programme (FTP) and a state corporation, Rusnano (formerly Rusnanotekh), which together would use the money to realise the aims of the development programme through investment in infrastructure and funding for R&D.

This large injection of state money had an immediate impact. Indeed, in 2009, when the money came online fully, Russia became the biggest spender globally. Only two thirds of that money went towards R&D, however. In the years leading up to the 2007 push, Russia had spent comparatively little on nanotechnology, and as a consequence a large proportion of the investment was need needed for basic development of the relevant infrastructure.

Cientifica estimated Chinese public spending on nanotechnology R&D at €960m (\$1.3bn) in absolute terms and €1.65bn (\$2.25bn) assuming purchasing power parity (ppp)<sup>40</sup>. With the US allocating only €1.6bn (\$2.18bn) to the field in 2011, China become for the first time the biggest spender globally.

Japan has a reputation as a country that invests heavily in R&D, and in relation to nanotechnology it has more or less played to type, spending €280m (\$380m) of public money on the field (Materials UK, 2010).

The Taiwanese government directed €88m (\$120m) of public money into nanotechnology R&D in 2010 (Materials UK, 2010).

<sup>40</sup> http://www.cientifica.com/research/white-papers/global-nanotechnology-funding-2011/

In 2007, the India government approved Nano Mission, a national nanotechnology R&D programme, with an allocation of €124m (Rs1000crore) for five years.

#### 4.2.2 Private

Several market research firms (Lux Research, Cientifica) have produced widely quoted reports on private spending on nanomaterial R&D but these are not readily available.

Additionally, not all companies publish their information about nanomaterials (ObservatoryNANO, 2011):

As it has been noted in this paper, companies do not always publicize their research in nanotechnology. In fact, depending on the industry, some companies are fearful of making it known. This factor not only may skew numbers such as the true count of nanotechnology companies, but it can also play an impact in driving (or discouraging) future nanotechnology research. If a company feels nanotechnology research will be punished rather than lauded, it will be more hesitant to pursue such developments. This is just one of many barriers a nanotechnology company may face. While barriers to commercial success have been identified, further investigation could be made to better understand the possible solutions to overcome such barriers.

It may be possible however to construct a qualitative picture of private spending by profiling companies with nanomaterial business and large R&D budgets.

BASF spent €1.8bn on R&D in 2013, split six ways, as shown in Table 4-3.

Table 4-3: BASF 2013 R&D spending by business segment			
Segment	Spending (€m)	Proportion of total (%)	
Chemicals	184	10	
Performance products	367	20	
Functional materials and solutions	367	20	
Agricultural solutions	477	26	
Oil and gas	55	3	
Corporate research, other	385	21	

The segments can be divided into sub-segments, as shown in Table 4-4. By inspection of the sub-segments, it might be expected that nanotechnology applications are most likely to be found in 'performance products' and 'functional materials and solutions'.

Table 4-4: BASF business segments and sub-segments			
Segment	Sub-segment	Description on BASF website <sup>41</sup>	
	Petrochemicals	Basic products: ethylene, propylene, butadiene, benzene, alcohols, solvents, plasticizers, alkylene oxides, glycols and acrylic monomers	
		Specialties: Special plasticizers such as Hexamoll® DINCH®, special acrylates	
Chemicals	Monomers	Basic products: isocyanates (MDI, TDI), ammonia, caprolactam, adipic acid, chlorine, urea, glues and impregnating resins, caustic soda, polyamides 6 and 6,6, standard alcoholates, sulfuric and nitric acid Specialties: Electronic chemicals, metal system	
	Intermediates	Basic products: butanediol and derivatives, alkylamines and alkanolamines, neopentylglycol, formic and propionic acid	
		Specialties: specialty amines such as tert-Butylamine, gas treatment chemicals, vinyl monomers, acid chlorides, chloroformates, chiral intermediates	
	Dispersions and pigments	Polymer dispersions, pigments, resins, high-performance additives, formulation additives	
	Care chemicals	Ingredients for skin and hair cleansing and care products, such as emollients, cosmetic active ingredients, polymers and UV filters	
		Ingredients for detergents and cleaners in household, institution or industry, such as surfactants, chelating agents, polymers and products for optical effects	
		Solvents for crop protection formulations and products for metal surface treatments	
Performance products		Superabsorbents for the hygiene industry	
renormance produces	Nutrition and health	Additives for the food and feed industries, such as vitamins, carotenoids, sterols, enzymes, emulsifiers and omega-3 fatty acids	
		Flavors and fragrances, such as geraniol, citronellol, L-menthol and linalool	
		Active ingredients and excipients for the pharmaceutical industry, such as caffeine, ibuprofen and pseudoephedrine as well as binders and coatings for tablets, synthesizing pharmaceutical substances and intermediates for our customers	
	Paper chemicals	Dispersions for paper coating, functional chemicals, process chemicals, kaolin minerals	

<sup>41</sup> http://www.basf.com/group/corporate/en/about-basf

Segment	Sub-segment	Description on BASF website <sup>41</sup>	
Performance products (cont.)	Performance chemicals	Antioxidants, light stabilizers, pigments and flame retardants for plastic applications  Fuel and refinery additives, polyisobutene, brake fluids and engine coolants, lubricant additives and basestocks, components for metalworking fluids and compounded lubricants  Process chemicals for the extraction of oil, gas, metals and minerals, chemicals for enhanced oil recovery, water treatment chemicals, membrane technologies  Auxiliaries for the production and treatment of leather and textiles	
	Catalysts	Automotive and process catalysts Battery materials Precious and base metal services	
Functional materials and solutions	Construction chemicals	Concrete admixtures, cement additives, underground construction solutions, flooring systems, sealants, solutions for the protection and repair of concrete, high-performance mortars and grouts, tile-laying systems, exterior insulation and finishing systems, expansion joints, wood protection solutions	
	Coatings	Coatings solutions for automotive and industrial applications Decorative paints	
	Performance materials	Polyurethane systems and specialty elastomers, engineering and high-performance plastics, biopolymers and epoxy resins, insulation and specialty foams	
	Fungicides	Protecting crops from harmful fungal attacks; improving plant health	
	Herbicides	Prevention of nutrient and water deprivation caused by weeds	
Agricultural solutions	Insecticides	Combating insect pests in agriculture	
	Functional crop care	Products beyond traditional crop protection for plant health and increased yield potential, such as biological control products, seed treatments, polymers and colorants	
	Pest control	Non-agricultural applications: public health, professional pest control, landscape maintenance	
0:1	Exploration and production	-	
Oil and gas  Natural gas trading		-	

#### Geographic distribution of R&D

One of BASF's stated aims is to move more of its R&D outside Europe. <sup>42</sup> In 2013, it conducted '28%' of its R&D outside Europe and it is aiming for 50% by 2020.

#### Key areas of interest

In its annual press release on innovation, BASF highlighted its interest in several nanomaterials and fields of nanotechnology R&D:

- Insulation materials. BASF markets polyurethane foams with nano-scale (50-100nm) pores.
- Microencapsulation. Active compounds, for a range of applications, can be encapsulated in a micro-scale shell of another substance, typically a wax, a polymer or an oil-based substance, to facilitate a delayed release profile. BASF is interested in nano-scale control of the shell thickness and nano-structuring of the shell as ways to fine-tune the release of the encapsulated compound.
- Graphene for use in organic light emitting diodes (OLEDs), electronic displays, batteries and catalysts.
- Colour filters for liquid display (LCD) components. BASF has manufactured filters comprising particles of less than 40nm in diameter.
- Nanomaterial toxicology and eco-toxicology.

#### Mode of action

BASF has partnered with many universities to conduct nanotechnology R&D. In 2013, for example, the company established an 'advanced materials' programme with three US universities: Harvard University, Massachusetts Institute of Technology and the University of Massachusetts, Amherst<sup>43</sup>. The referenced source (a press release) suggests that a significant part – if not all – of the funded R&D might be considered nanotechnology R&D:

Topics already identified include micro- and nanostructured polymers with new properties, as well as biomimetic materials that emulate nature. For example, the scientists are working on lightweight construction materials for wind turbines and automotive construction and on new color effects for cosmetic applications.

One part of the programme is about 'pharmaceutical nano-formulations' 44.

BASF did not disclose the amount of money it was contributing when it announced the programme, but it said that it would fund 20 post-doc positions over the five year period. The move built on a €15m (\$20m) 2007 programme between BASF and Harvard that focused on biofilms and chemical formulations for drugs, food and cosmetics.

http://www.basf.com/group/pressrelease/P-14-237. The source document (a press release) does not indicate the measure of R&D used for the percentage. We assume the figure is based on R&D spending.

http://www.basf.com/group/corporate/en GB/news-and-media-relations/news-releases/news-releasesusa/P-13-291.

http://research.initiative.seas.harvard.edu/research.html

#### Solvay

Solvay is a major international chemical company with nearly 30,000 employees in over 50 countries. It also has 15 research and innovation (R&I) centres with 2,000 staff and spends nearly €250m per annum on R&I as shown in Table 4-5.

Table 4-5: Solvay 2013 R&I spending by business segment		
Segment	Spending (€m)	Proportion of total (%)
Performance Chemicals	20	8.4%
Advanced Formulations	52	21.9%
Advanced Materials	90	38.0%
Functional Polymers	22	9.3%
Corporate & Business Services	53	22.4%
Total	237	100.0%
Source: http://www.solvay.com/en/binaries/2013-annual-report-EN-164627.pdf		

#### Priorities for Nanotechnologies

Solvay is keen to develop nanomaterials and nanotechnology within three broad areas<sup>45</sup>:

- · electronics and IT
- manufacturing and materials
- healthcare and life sciences.

Some examples of specific applications are presented in Table 4-6. No published information is available as to the levels of R&I expenditure in these specific areas.

Table 4-6: Solvey Development in Nanomaterials		
Material Classification	Material	Specific Examples
	Fluorides – Superfine	MgF2, CaF2, BaF2, TiOF2
Nanomaterials	Nano Barium Sulfate	Improvement to resistance to scratch, abrasion, impact etc., hardness, rigidity etc.
		Keeps transparency in resins, varnishes, and polymers – polycarbonate, acrylic, epoxy, polysulfone
	Nano-PTFE	Microemulsion (10.60 nm particle size)
		PTFE bimodal dispersion for coating
	Precipitated Calcium Carbonate	

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Miltner H (2010): The potential of Nanotechnologies for SOLVAY, a Chemicals and Pharmaceuticals Company, presentation available from: <a href="https://eng.kuleuven.be/studenten/programma/interdepmasters/nanotechnology/HEM-SOLVAY\_IMEC-Apr26-2010.pdf">https://eng.kuleuven.be/studenten/programma/interdepmasters/nanotechnology/HEM-SOLVAY\_IMEC-Apr26-2010.pdf</a>

Table 4-6: Solvey Development in Nanomaterials		
Material Classification	Material	Specific Examples
Nano-intermediates	NanoVin® a commercialised product	Plastisols for thick coating, soft grip for tooling
	Functional PerFluoroPolyEthers	Soft Lithography refers to a group of techniques for micro- and nano-fabrication using a soft elastomeric stamp – applications include Microlenses, Microfluids, etc.
		PFPEs functionalised with reactive end- groups (Flurolink MD700, 5112X) are ideal raw materials for manufacturing elastomers
Nano-enabled products	Fenofibrate	Used for the treatment of Dyslipidemia

Source: https://eng.kuleuven.be/studenten/programma/interdepmasters/ nanotechnology/HEM-SOLVAY\_IMEC-Apr26-2010.pdf

#### **Other Large Companies**

Research into a number of other large companies (including Evonik, Air Liquide, Linde, Yara, DSM and AkzoNobel) indicated significant expenditure on R&D (or R&I) with some companies providing information on their development of nanotechnologies. However, specific data on R&D expenditure on nanomaterials/nanotechnologies were not readily available.

#### **SMEs**

Nanomaterials and nanotechnologies are also being developed and implemented by small and medium sized enterprises (SMEs). Investigation into several likely SMEs was undertaken by reviewing information on companies claiming to manufacture nanomaterials on the Nanowerk website<sup>46</sup>.

As for the large companies considered above, it was possible to derive some basic company information (size, products, etc.) and areas of interest in nanomaterials. However, no specific data on R&D expenditure on nanomaterials/nanotechnologies were identified. Some examples are listed in Table 4-7.

Table 4-7: Examples of SMEs involved in Nanotechnology		
Company (Country)	Main Activity	Comment
CAN GmbH (Germany)	Production of various nanoscaled materials like fluorescent, magnetic and catalytically-active nanocrystals. Also undertake consulting and contract research	These products are marketed under the brand CANdots and are dispersible in polar or unpolar media readily available for applications in research and industry.

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http://www.nanowerk.com/nanotechnology/nanomaterial/suppliers\_plist.php?page=1& mat=&subcat1=np

Table 4-7: Examples of SMEs involved in Nanotechnology			
Company (Country)	Main Activity	Comment	
IBU-tec advanced materials (Germany)	Manufacturer of nanopowders.	12.5% of their employees do research and development	
MBN Nanomaterialia S.p.A. (Italy)	Producer of nanopowders such as nanostructured metal alloys, ceramics and metal-ceramics nanocomposites, polymeric alloys, fillers and nanostructured additives	Active at EU level through Nanofutures platform	
Metal Nanopowders (UK)	The company is dedicated to the production of metal powders at the sub-100nm scale.	A spin-off from the University of Birmingham	
Particular (Germany)	The company manufactures custom nanoparticle dispersions and also provides nanoparticle coating for metallic products, for instance for medical instruments.		
Yorkshire Bioscience (UK)	The company provides services and reagents for molecular biology research. Among its products are nanodiamonds.		

Sources:

CAN GmbH (Germany): http://www.can-hamburg.com/english/home.html

IBU-tec advanced materials (Germany): <a href="http://www.ibu-tec.de/">http://www.ibu-tec.de/</a>
MBN Nanomaterialia S.p.A. (Italy): <a href="http://www.mbn.it/eng/">http://www.mbn.it/eng/</a>
Metal Nanopowders (UK): <a href="http://www.metalnanopowders.com/">http://www.metalnanopowders.com/</a>
Particular (Germany): <a href="http://particular.eu/startseite.html">http://particular.eu/startseite.html</a>

Yorkshire Bioscience (UK): <a href="http://www.york-bio.com/">http://www.york-bio.com/</a>

#### 4.2.3 Strategic priorities

A multitude of programmes and organisations within the EU are currently spending public money on nanotechnology R&D. A comprehensive quantitative analysis of the strategic priorities of all of these is beyond the scope of this report. It is, however, possible to gain a picture of this environment via a qualitative analysis of an indicative programme or group of programmes.

Germany spends the most on nanotechnology R&D, publishes the most journal articles and applies for the most patents. Furthermore, most of public money for nanotechnology R&D in Germany is delivered via the national R&D programmes.

It seems reasonable, therefore, to treat the strategic priorities of the German national nanotechnology R&D programme and its predecessors as indicative of those of programmes and organisations elsewhere in Europe.

In 2007, the German Ministry of Education and Research (BMBF) published a national strategy for nanotechnology R&D, the Nano-Initiative Action Plan 2010. This gave five key objectives:

- Opening up future markets, introducing new sectors
- Improving general conditions
- Behaving in a responsible manner
- Informing the public
- Identifying the future demands for research

The first of these, 'opening up future markets, introducing new sectors', was broken down as follows:

- Branch level industrial dialogues<sup>47</sup>
- Lead innovations
- Promoting networking
- Supporting SMEs

In 2011, the BMBF followed up the 2007 strategy with the Action Plan Nanotechnology 2015, which committed Germany to:

- Use nanotechnology to contribute to growth and innovation in Germany
- Make nanotechnology safe and sustainable
- Tap the potential of nanotechnology in education and research
- Tap the potential of nanotechnology to meet global challenges

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The programme aims to:

- Secure the contributions of nanotechnology to the protection of environment and climate, to securing of energy supply and to the creation of a knowledge-based bioeconomy
- Utilise the possibilities of nanotechnology for health
- Use the possibilities of nanotechnology for sustainable agriculture and food safety
- Achieve environmental and energy-saving mobility through nanotechnology

Table 4-8 shows the focus of research funding around so-called global challenges.

Table 4-8: Global challenges under the German Action Plan Nanotechnology 2015				
and for h		Nanomaterials for adaptive building technology	New high insulation and fireproof materials	
			Thermochromic house paints	
	Nanotechnology		Passive and active smart glazing	
			Micro-mirror arrays	
	for higher energy efficiency		Switchable insulation materials or phase change materials as latent heat accumulator	
		Nanomaterials for decentralised energy supply	Nanomaterials for electrical and thermal energy storage	

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These should help industrial sectors to understand the opportunities offered by nanotechnology to explore the ways in which nanotechnology might be used. They would focus on sectors with little previous access to the results of nanotechnology R&D and in particular SMEs within those sectors. Dialogues should be carried out in the following areas: automotive, construction, textiles, IT, the life sciences, optics, chemistry, energy and the environment.

Table 4-8:	Global challenges un	der the German Action P	lan Nanotechnology 2015	
	Nanotechnologies for the adaption to climate		Water filtering	
		Development of	Catalytic processes associated with water filtering	
		filtering techniques	De-salination of sea water	
	changes	Improvement of hygiene	Filters for hygiene requirements	
		NanaNatura	Procedures for water and air cleaning, soil rehabilitation and water treatment	
		NanoNature: Nanotechnologies for the protection of the environment	Procedures for product preparation, resource recovery and environmentally friendly separation processes	
			Methods for the reduction of discharges of substances into the environment	
		Material efficiency,	Nanotechnologies enabling substitution of scarce raw materials	
		substitution of scarce raw materials and	More material-efficient recycling through joining technologies, such as nanobonding	
		recycling	Nanocatalysts for alternative chemical reaction paths	
		Carbon nanomaterial	Impact of carbon nanotubes on human health	
	Protection of	<ul><li>substitution and efficiency</li></ul>	Conservation of natural resources through the use of carbon nanomaterials	
	environment and resources	Low wear and environmentally friendly friction materials	Lubricating technologies that enable better performance and lower impact on the environment	
		New materials for	Efficient nanofiltration membranes	
		sustainable water management	Environmentally friendly reagents and catalysts	
			Nanomaterials for adsorptive procedures	
		Funding activity "Nano goes Production"	Environmentally friendly production of nanomaterials	
		New and safe components through multiscale simulation	Simulation of nanoscale properties behaviour of materials for improved products and production processes	
		Survey on potential reduction of environmental pollution	Tools for the evaluation of life-cycle benefits enabled by nanotechnologies including, efficient use of raw materials, reduced energy consumption and reduced emission of pollutants	
	Health		Diagnostic tools (nanoparticle contrast agents, sensors)	
Health– nutrition		Molecular imaging	Imaging methods	
			Pharmaceuticals	
			Theranostics	
		Tailor-made therapies	Controlled release coatings and matrices	
and		and nano-medicine	Drug delivery systems	
agriculture		Personalised implants and prostheses for long-term rehabilitation	Enhanced implants with improved tissue compatibility	
		Regenerative	Nanotechnologies and nanomaterials for	

Table 4-8: (	Global challenges ur	der the German Actio	on Plan Nanotechnology 2015	
		medicine and nanostructured biomaterials	replacement tissues and organs	
		Nanotechnology for improved plant protection products and methods		
		Controlled carrier systems for the specific release of active agents for defined physical or chemical impacts		
		Impact assessment of nanomaterials for controlled application in agriculture (risk assessment of the chemical, physical and ecotoxicological properties of active agents and carrier agents and of their discharge into the ecosystem as well as discharge of the raw material flows		
	Nutrition and agriculture		quicker, more cost-effective and precise diagnostic of animal and plant diseases	
		Analysis methods for the detection and quantification of nanoscale food ingredients		
		Easy-to-clean nanocoated surfaces in food storage, transport and processing		
		Nanotechnology for	functional food packaging	
		Nanotechnology for increased bioavailability of desired food ingredients		
		Nanotechnologies for energy generation from renewable sources linked to agriculture		
		Nanotechnology for cost-effective and resource-	Filters and cleaning components for exhaust fumes	
			Lightweight components	
			Catalysts	
		saving mobility	Coatings for injection systems	
			Components for injection systems	
Mobility		Nanotechnology for electric mobility	Electrode and conductor materials for energy storage (via batteries) and transport	
			Super-capacitor components	
			Nanomaterials for hydrogen fuel cells	
		Nanomaterials for	Sensors for road-to-car communication	
		intelligent streets	Transport infrastructure materials with noise reducing properties	
Communication		Quantum communication as a basis for tap- proof communication	Quantum repeaters for secure data transfer	
		Organic or	Income and alignments	
		Organic or	Improved displays	
		Organic or printable electronics	OLEDs OLEDs	

Table 4-8: Global challenges under the German Action Plan Nanotechnology 2015			
	Document protection and product security through product identification and marking systems for the generation of optical security features	Fluorescent nanoparticles for product identification and marking systems	
		Biological materials for security inks	
	Development of nanotechnological materials for the managing of potential consequences of major incidents	Improved decontamination products	
		Filters	
Security		Self-cleaning nanostructured surfaces	
		Catalytically active nanoparticles for coatings	
	Development of stab and bullet-proof nanoscale materials for protection systems for policemen and rescue workers	Integrated protection systems for the protection against hazardous substances, explosion impacts, fires and projectiles	
		Polymer nanocomposites (shock-proof carbon nanotube fibers, shear-thicking nanofluids) for staband bullet-proof textiles	
		Clothes with self-healing properties	

### 4.3 Patents

# 4.3.1 Introduction

Patents applications and approvals might be used as a proxy for innovation. This approach has some well documented limitations (see 'Proxies for innovation'), but can be informative nonetheless provided it is neither viewed in isolation nor over interpreted.

Previous reports on the status of nanotechnology have included discussions on patents. Typically, however, the most recent data used for these is from 2010. The European Nanotechnology Landscape Report, for example, examined patent data from 2000 to 2010. Its findings can be summarised as follows:

- Germany filed many more nanotechnology patents than any other country. Indeed, the number of patents applications filed by Germany (3730) is almost equal to the number of patents filed by the other EU member states combined (3767).
- The states publishing high numbers of nanotechnology journal articles (Germany, the UK, France) are also filing high numbers of patent applications.
- The Netherlands stands out as a country that produces more patent applications than journal articles. In general, countries produce more of the latter.
- There is considerable variation between sectors in terms of patent applications. Some produce a lot others, very few.

Historically, separating the data on patents relating to nanotechnology from wider the data on patents has not been straightforward and as such the research community has made many attempts to design the best possible strategy for the identification of nanotechnology patents (Zheng *et al*, 2014). The USPTO<sup>48</sup> recently created over 250 cross-reference art collection subclasses in Class 977, Nanotechnology<sup>49</sup>, intended to provides for disclosures:

- Related to research and technology development at the atomic, molecular or macromolecular levels, in the length of scale approximately 1-100 nanometer range in at least one dimension
- That provide a fundamental understanding of phenomena and materials at the nano-scale and to create and use structures, devices and systems that have novel properties and functions because of their size.

This class features in the 'Calendar Year Patent Statistics General Patent Statistics Reports Available For Viewing' in the Patent Counts By Class By Year'<sup>50</sup>. It does not, however, appear on the list of classes with 'Patenting In Technology Classes Breakouts By Geographic Origin (State and Country)'<sup>51</sup>.

Meanwhile, patent offices worldwide have started to classify nanotechnology uniformly under the International Patent Classification (IPC) system<sup>52</sup>. A new symbol, B82Y, was introduced into the IPC on 1 January 2011, replacing the Y01N symbol used previously by the EPO. These tags could be used in conjunction with appropriate keyword-search strategies to generate data on patents relating to nanotechnology (Zheng *et al*, 2014).

The OECD produces such data across the following areas:

- Patent applications to the EPA, years to 2010
- Patent grants at the USPTO, years to 2008
- Triadic patent families, years to 2010
- Patent applications filed under the Patent Co-operations Treaty (PCT), years to 2011
- Patent grants at the EPO, years to 2008

Statnano, part of the Iranian Nanotechnology Council Initiative, produces data on patents relating to nanotechnology, based on Orbit.com, a full-text patent search system familiar to independent information professionals (Wolff & Adams, 2010).

According to Figure 4-1, which is based on Statnano data, 21,379 patents related to nanotechnology were granted by the USPTO in 2013, representing a 60% increase compared with 2012. According to the USPTO, in 2013, the US had a share of 57% of all patents issued, which (unsurprisingly) is more

<sup>&</sup>lt;sup>48</sup> United States Patent and Trademark Office (USPTO)

http://www.uspto.gov/patents/resources/classification/class 977 nanotechnology crossref\_art\_collection.jsp

http://www.uspto.gov/web/offices/ac/ido/oeip/taf/cbcby.htm

http://www.uspto.gov/web/offices/ac/ido/oeip/taf/tecstc/classes\_clstc\_gd.htm

http://www.epo.org/news-issues/issues/classification/nanotechnology.html

than the sum of all other countries. This is followed by Japan with a 15% share and the EU28 with a 14% share (as broken down in Table 4-9). The rest of the world had almost the same share of patents issued as the EU28, where the majority of the patents were issued to China, Taiwan, Switzerland and South Korea.

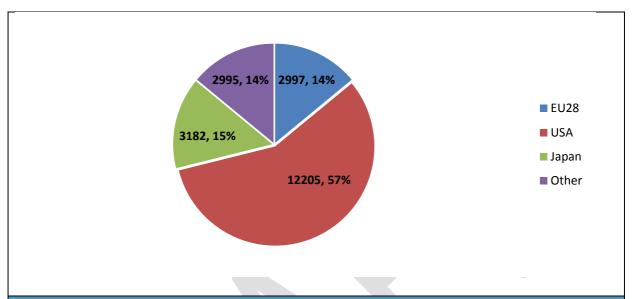


Figure 4-1: Number of patents issued by the USPTO in 2013

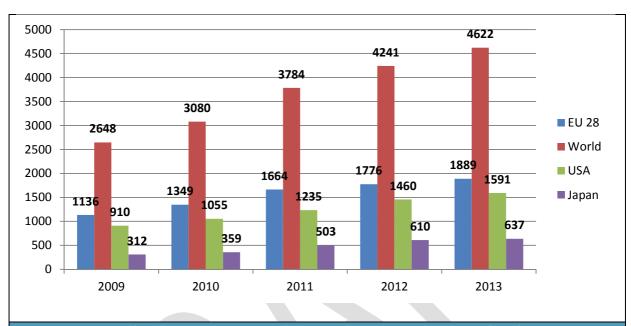
**Source:** Nano Statistics (2014): Nanotechnology published patent applications in USPTO. Available at http://statnano.com/report/s89 on 17 February 2014.

Table 4-9: Number of patents issued by the USPTO in 2013 to EU28 member states				
EU member state	member state Number of patents 2013		Number of patents 2013	
Germany	886	Portugal	7	
France	561	Czech Republic	7	
Netherlands	397	Estonia	5	
UK	266	Hungary	5	
Belgium	113	Romania	3	
Italy	97	Cyprus	3	
Sweden	82	Poland	2	
Denmark	63	Slovenia	2	
Ireland	62	Lithuania	2	
Finland	61	Croatia	2	
Spain	39	Bulgaria	1	
Austria	37	Latvia	0	
Luxembourg	21	Slovakia	0	
Greece	eece 8		0	

**Source:** Nano Statistics (2014): Nanotechnology published patent applications in USPTO. Available at http://statnano.com/report/s89 on 17 February 2014.

As can be seen, the number of patents to some extent corresponds to the size of the country as well as the level of industrialisation.

For another perspective, we also looked at the number of patents issued by the European Patent Office (EPO). From Figure 4-2, it can be seen that in 2013, the EPO issued 41% of all patents to EU28 member entities, which is slightly lower than in 2012, when 42% of patents were issued to EU member states, even though the number of patents issued increased 4,622 (in 2013) from 4,241 (in 2012).



**Figure 4-2:** Number of patents issued by the EPO (2009-2013) *Source:* Nano Statistics (2014): Nanotechnology published patent applications in EPO. Available at http://statnano.com/report/s95 on 17 February 2014.

In Table 4-10, we present the number of patents issued by the EPO to individual EU28 member states for the period 2009 to 2013. Again Germany leads the pack with a share of 41% of all patents issued by EPO in 2013. This is disproportionately high with respect to other EU member states; Germany had, for example, twice as many patents issued as the second placed France. This highlights the fact that Germany seems to be the innovation leader in terms of nanotechnology patents. Following France are the Netherlands, the UK and Belgium. In others words, the most industrialised countries in the EU28 produce the most patents by this measure.

Table 4-10: Total number of patents issued by the EPO to EU28 member states (2009-2013)					
	2009	2010	2011	2012	2013
EU 28	1136	1349	1664	1776	1889
Germany	430	484	665	693	775
France	233	288	368	344	379
Netherlands	124	147	157	188	182
UK	83	110	130	136	151
Belgium	51	60	76	84	76
Italy	66	67	60	92	70
Sweden	34	37	45	58	55
Denmark	27	46	54	51	51

Table 4-10: Total number of patents issued by the EPO to EU28 member states (2009-2013)					
	2009	2010	2011	2012	2013
Austria	20	32	26	40	40
Spain	17	12	24	24	31
Finland	15	27	12	24	23
Ireland	14	16	20	15	16
Luxembourg	7	4	5	5	10
Czech republic	4	6	7	3	9
Slovenia	0	0	4	2	5
Greece	4	1	3	1	5
Poland	3	2	0	7	4
Portugal	0	2	3	2	3
Lithuania	0	1	0	0	2
Hungary	1	3	3	2	1
Latvia	0	1	1	0	1
Cyprus	1	1	0	0	0
Romania	0	0	0	0	0
Croatia	2	1	0	1	0
Estonia	0	0	1	3	0
Slovakia	0	1	0	1	0
Bulgaria	0	0	0	0	0
Malta	0	0	0	0	0

**Source:** Nano Statistics (2014): Nanotechnology published patent applications in EPO. Available at <a href="http://statnano.com/report/s95">http://statnano.com/report/s95</a> on 17 February 2014.

# 4.4 Scientific Literature

Based on analysis of 1998-2009 data (ObservatoryNANO, 2011), the countries publishing the most nanotechnology journal articles are Germany, the UK, France and Switzerland. Each of these countries published over 1000 such articles from 1998 to 2009. Together, they accounted for two thirds of the total. Table 4-11 shows the full data set:

Table 4-11: Nanotechnology journal articles published by country from 1998 to 2009		
Country	Number of articles	
Switzerland	1031	
Finland	494	
Sweden	816	
Germany	6449	
Austria	590	
United Kingdom	2688	
Netherlands	650	
Denmark	191	
Ireland	151	
Belgium	319	
Estonia	39	
France	1491	
Slovenia	40	

Table 4-11: Nanotechnology journal articles published by country from 1998 to 2009		
Country	Number of articles	
Czech Republic	191	
Hungary	180	
Luxembourg	8	
Italy	955	
Cyprus	12	
Greece	161	
Lithuania	35	
Slovakia	56	
Spain	409	
Bulgaria	56	
Poland	280	
Portugal	73	
Romania	71	
Latvia	7	
Source: (ObservatoryNANO, 2011)		

#### 4.5 **Future Market Trends**

Nanotechnology is regarded as being one of the technologies from which a great deal of future growth will be generated. In this sense it has been defined as a Key Enabling Technology (KET) and represents one of the elements which will generate a great proportion of future employment growth, research and development and technological innovation.

Cientifica identified four countries with the combination of academic excellence, technology-hungry companies, a skilled workforce and the availability of early stage capital to ensure effective technology transfer<sup>40</sup>: Germany, the US, Japan and Taiwan.

The quantification of the effects that nanotechnology has on the economy is subject to much research and speculation. According to some studies nanotechnology impacted € 182.7 billion<sup>53</sup> (US\$ 254 billion) worth of products in 2009 and this impact is forecasted to grow to € 1.799 trillion<sup>5</sup> (US\$ 2.5 trillion) by 2015<sup>54,55</sup>. Older Lux Research's estimates from 2007 predict that the size of the global market size, assuming steep growth, would reach € 1.9 trillion<sup>56</sup> (US\$ 2.6trillion) in 2014, which was 70% higher than their original estimate from 2005<sup>57</sup>. However, the economic crisis occurring since 2008 has decreased somewhat the estimations of nanotechnology market size. Lux Research estimated in 2009 that the global market size of nanotechnology would be € 1.799 trillion<sup>5</sup> (US\$ 2.5 trillion) by 2015, which is 4 % less than the 2007 estimates. In this context particularly the

CEFIC (2010): Nanotechnology: A sustainable basis for competitiveness and growth in Europe. Dated December 2010. Available at http://ec.europa.eu/enterprise/sectors/ict/files/kets/3 nanotechnology final report en.pdf on 17 February 2014.

Using average ECB exchange rate for 2009 i.e. \$/€ 1,39

Lux Research and Forfás (2010): Ireland's Nanotechnology Commercialisation Framework 2010-2014. Dated August 2010. Available at http://www.forfas.ie/media/forfas310810nanotech commercialisation framework 2010-2014.pdf on 17 February 2014.

Using average ECB exchange rate for 2007 i.e. \$/€ 1,37

Lux Research (2007): The Nanotech Report 2006: Investment Overview and Market Research for Nanotechnology. New York: Lux Research Inc.

decline in the cyclical automobile and construction industries was estimated to have the strongest negative effect on demand for nanotechnology and particularly on nanomaterials and composites<sup>58</sup>.

As a result of the above described trends, the number of workers employed in the nanotechnology sector worldwide is expected to reach 2 million by 2015, of which 0.8-0.9 million would be in the United States and 0.3-0.4 million in Europe<sup>59</sup> (see Figure 4-3). Other estimates state that the estimated number of nanotechnology jobs is to reach 1 million in the US by 2014<sup>60</sup>.

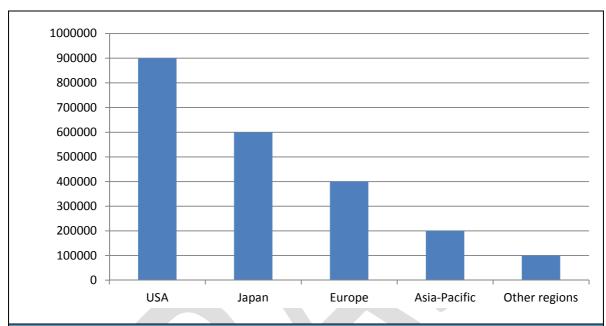


Figure 4-3: Number of Nanotechnology jobs by 2015 globally

**Source:** OECD (2009): Nanotechnology: an overview based on indicators and statistics. Dated 25 June 2009. Available at http://www.oecd.org/dataoecd/59/9/43179651.pdf on 17 February 2014.

Nanotechnology is expanding its reach to different economic categories such as consumer goods, aerospace, medicine, automobile industry etc. and is regarded as being one of the technologies of the future. It affects an ever increasing part of economic production and according to some studies nanotechnology impacted €183 billion<sup>5</sup> (US\$ 254 billion) worth of products in 2009, which is projected to grow to around €1.8 trillion<sup>5</sup> (US\$ 2.5 trillion) by 2015.

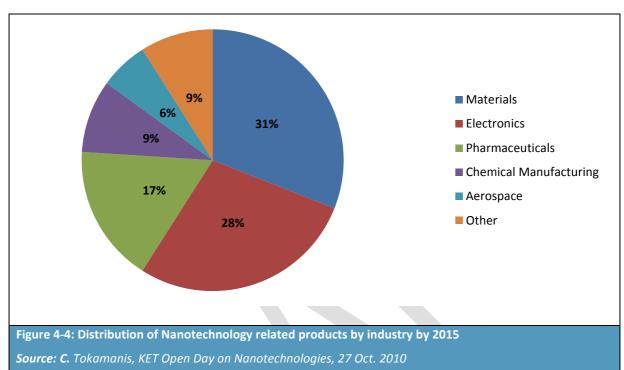
The global market for nanotechnology (on its own) is valued at about € 14.9 billion in 2012 and is expected to increase to more than € 18.9 billion in 2015 and € 35.2 billion in 2017. As indicated in Figure 4-2 and Table 4-1, the largest segment of nanotechnology are nanomaterials. The market for nanomaterials stood at about € 6.6 billion in 2009 and is expected to increase to more than € 14.3 billion in 2015 and € 26.8 billion in 2017.

Lux Research (2010): The Recession's impact on Nanotechnology. Boston: Lux Research Inc.

<sup>&</sup>lt;sup>59</sup> Christos Tokamanis, KET Open Day on Nanotechnologies, 27 Oct. 2010

OECD (2012): The Economic Contributions of Nanotechnology to Green and Sustainable Growth. Dated 12 March 2012. Available at http://www.oecd.org/sti/nano/49932107.pdf on 17 February 2014.

Research for the National Science Foundation (NSF) in the United States looked at a range of scenarios for the potential world market for nanotechnology in 2015 with estimates ranging from conservative € 376 billion to the more "optimistic case" of 1.5 trillion. As indicated in Figure 4-4 the majority of nanotechnology will be applied in materials (nanomaterials) and electronics, where they will represent an estimated 31 % and 28 % respectively. Other segments where nanomaterials will be applied to use are also the pharmaceutical industry (17%), chemical manufacturing (9 %) and Aerospace (9%).



# 4.6 Emerging Nanomaterials, their Properties and Applications

### 4.6.1 Introduction

The volume and diversity of nanomaterials, nano-scale phenomena and applications under investigation is very large indeed. They include, for example:

- Quantum dots for use as bio-imaging agents
- Ferrofluids
- Anti-counterfeiting products
- Printed electronics
- Nano-enabled sensors for security applications
- Self-cleaning, super-hydrophilic thin films
- Anti-bacterial silver nanoparticles
- Gold nanoparticles
- Carbon nanotubes
- Mesoporous silica nanoparticles drug delivery
- Hierarchical nanoparticle assemblies
- Metamaterials
- Anti-biofouling paints for boats
- Surfaces that reduce build-up of snow on antennas and windows

- Self-cleaning windshields for automobiles
- Microfluidic components
- Lab-on-a chip devices

The following discussion is in intended to give a qualitative picture of the field only. It should not be considered comprehensive

# 4.6.2 The lotus effect, super-hydrophobicity and related phenomena

Many surfaces show some resistance to water as a result of the bulk properties of the material from which they are made. Others can be made resistant to water (or more resistant) by some kind of surface modification. Another substance, such as a fluorinated surfactant, might be applied to the surface, for example. Alternatively, increased resistance to water might be induced by modification of the morphology of the surface.

Specifically, nano-scale surface structures can be used to replicate the lotus effect, named after the leaves of the lotus flower, which exhibit an usually high resistance to water and can be thought of as super-hydrophobic. The key values relating to the super-hydrophobicity of a surface are contact angle, roll off angle, the degree to which water will 'bounce' off the surface and surface energy.

The contact angle is the angle between the liquid–surface interface and the liquid–air interface for a droplet of liquid on a flat surface. A high contact angle means that the liquid is more spherical: it sits up on the surface as a distinct bead, rather than flattening out across a large area. The roll off angle is the deviation from horizontal required for gravity to make the droplet move without agitation (roll off the surface).

By convention, a surface is considered super-hydrophobic if the contact angle with water exceeds 150° and the roll-off angle with water is less than 10°.

Surface morphology is the driving force behind super-hydrophobicity: nano-scale structures give the material a two phase (solid—air) surface layer that resists wetting without deviation from the bulk chemistry of the substrate. That said, traditional chemistry typically plays a role as well. In most cases, the surface has been chemically altered (functionalised) to resist wetting by lowering the surface energy.

This has implications for commercial viability. A combination of two laboratory processes (texturing and chemical finishing) is likely to be more technically challenging and more expensive to scale up than one laboratory process running in isolation. Furthermore, the most commonly used compounds for the chemical finishing of the roughened surfaces, fluoroalkylsilanes, are expensive and potentially harmful to human health and the environment. Finishing with stearic acid treatment is a viable alternative in some cases, such as cotton textiles roughed with particles of titanium dioxide or silica (Xue, Jia, Zhang, & Ma, 2010). In other cases, polymer coatings can be used instead of chemical finishing. It is possible, for example, to successfully finish a super-hydrophobic fabric nano-textured with silica particles using a styrene based polymer.

Phenomena closely related to super-hydrophobicity can also be induced by the nano-scale surface structures used for super-hydrophobicity or very similar ones. Surfaces might for example be made:

- Oleophobic, meaning the surface resists oil
- Solvent resistant

- Omni-phobic (or stain resistant), meaning the surface resists 'everything', usually taken to mean water and oil
- Self-cleaning (or dust resistant). Super-hydrophobic surfaces<sup>61</sup> with very high contact angles can be cleaned by the action of beads of water rolling across them
- Anti-microbial

Nano-scale structures can made out of the same material as the substrate. The structures might be the product of removing material from a un-textured surface (etching) or they might have been grown on a un-textured surface using the same material.

Specifically, nano-scale structures can be chemically etched into rigid surfaces (silicon, copper, nickel, magnesium) using acids (monoalkyl phosphonic acid, nitric acid, sulphuric acid) and bases (potassium hydroxide) to induce super-hydrophobicity. This approach has good industrial scale up potential by virtue of being based on the reactions of bulk chemicals (Latthe, Gurav, Maruti, & Vhatkar, 2012). In one study, researchers etched copper to generate surfaces that were not only super-hydrophobic but also highly resistant to corrosive liquids. Such surfaces, might greatly extend the application of copper in many important industrial fields (Latthe, Gurav, Maruti, & Vhatkar, 2012).

Additionally, plasma treatment can be used to etch rigid surfaces (glass, polystyrene) and induce super-hydrophobicity. A relevant process for glass substrates has been successfully tested. The process did not require vacuum instruments and was performed in an in-line, rather than batch, mode, making it potentially highly suitable for large areas and continuous processing units (Latthe, Gurav, Maruti, & Vhatkar, 2012).

Although it is more usual to deposit a different material, processes for the production of nanotextured surfaces by deposition of the substrate material onto the unadulterated surface are also described in the journal literature.

Commonly, nano-textured surfaces comprise nano-scale structures of one material on a substrate of a different material. Surfaces can be textured with nano-scale structures by electrochemical deposition. Metals and metal oxides are typically used. In some cases, the resulting surfaces are sufficiently liquid resistant to be of scientific interest without further manipulation; in others, chemisorption of another substance completes the process. Super-hydrophobic and omni-phobic surfaces can be made this way.

Zinc oxide nano-structures can be grown on various surfaces using basic solutions containing zinc ions. Silicon wafers, glass slides and polymer sheets have all been successfully used as substrates with. This approach is attractive in terms of industrial scale up for two reasons: it needs only bulk chemicals and it works on substrates with irregularly shaped surfaces, such as curved surfaces. It could be useful, for example, for aircraft, boats and some special decorative structures (Xue, Jia, Zhang, & Ma, 2010). Researchers have generated super-hydrophobicity on cotton fabric surfaces by growing zinc oxide nano-rod arrays by hydrothermal synthesis:

This method showed very good reproducibility and involved inexpensive laboratory equipment used for conventional textile processing (Xue, Jia, Zhang, & Ma, 2010).

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Note, some self-cleaning surfaces are not super-hydrophobic but the opposite, namely super-hydrophilic. (See 'Self-cleaning, super-hydrophilic thin films'.)

Others have grown tungsten oxide films on alumina plates and tungsten foils. They were able to induce rapid, reversible changes in the wettability, reaching super-hydrophilic at one end of the scale and super-hydrophobic at the other: switching between extremes took 25 minutes in one direction and just 30 seconds in the other. Surfaces with such properties could find applications in smart devices (Latthe, Gurav, Maruti, & Vhatkar, 2012). In general, hydrothermal synthesis is simple to control, is cost-effective and has a wide range of potential applications (Latthe, Gurav, Maruti, & Vhatkar, 2012).

Porous polymer membranes with durable hydrophobicity can be made by running polymerisation reactions in colloidal systems of two or more immiscible solvents, an approach called phase separation. This is a relatively simple and cost-effective approach (Latthe, Gurav, Maruti, & Vhatkar, 2012):

Phase separation has received great interest for the fabrication of superhydrophobic surfaces owing to its low cost, ease of production and the possibility of creating substrates with various shapes by casting and coating (Xue, Jia, Zhang, & Ma, 2010).

Additionally, it is possible to introduce luminescence to surfaces produced by phase separation, which could be of interest in relation to super-hydrophobic LEDs and road signs designed to be visible in low light conditions.

Self-assembly and layer-by-layer (LBL) deposition are two 'easy and economical' (Latthe, Gurav, Maruti, & Vhatkar, 2012) methods for preparing super-hydrophobic surface structures. For example, it is possible to make transparent, super-hydrophobic coatings by self-assembly of silica particles under mild conditions, and without template molecules, in just half an hour — using a process that 'has advantages for large-scale coating' (Latthe, Gurav, Maruti, & Vhatkar, 2012). The elements of this process have been extensively studied and developed in the microelectromechanical systems (MEMS) industry. Researchers have found a similar self-assembly process 'simple and potentially usable to fabricate large-area super-hydrophobic surfaces for practical self-cleaning applications' (Latthe, Gurav, Maruti, & Vhatkar, 2012). LBL deposition is based on the electrostatic charge interactions, is 'easy to perform' and allows for control of the thickness of the resulting layer with molecular precision (Latthe, Gurav, Maruti, & Vhatkar, 2012).

Super-hydrophobic cotton fabrics can be made by electrostatic LBL deposition of silica nanoparticles followed by treatment with a fluorinated compound. The buoyancy of the fabric was examined by making a miniature boat made out of it and the boat 'exhibited a remarkable loading capacity' (Latthe, Gurav, Maruti, & Vhatkar, 2012). In addition, the cotton fabric showed 'reasonable durability' with respect to washing, enduring 30 machine wash cycles. Rigid glass surfaces can also be made super-hydrophobic using LBL deposition.

Possibly the simplest of all the routes to nano-textured super-hydrophobic surfaces, solution immersion, as the name suggests, involves repeatedly dipping the substrate in an appropriate solution. This approach is quick, cheap and easy to do, and it does not require special equipment. It can be applied to rigid surfaces (copper, zinc) with copper or silicon compounds or flexible materials, such as those made from cellulose fibres.

Gaseous reagents can be deposited onto appropriate substrates to form non-volatile solid films through chemical vapour deposition (CVD). Researchers have made nano-textured superhydrophobic surfaces with CVD by growing a variety of materials (silicon compounds, carbon nanotubes) onto metal (aluminium, titanium, porous stainless steel mesh) surfaces. The stainless steel meshes treated in this way turned out not only super-hydrophobic but also super-oleophilic: water was repelled but oils (gasoline, iso-octane) permeated readily. This suggests such surfaces

could be used in filtration applications. Self-cleaning properties can be induced on rigid surfaces alongside super-hydropicity by depositing nano-rod arrays with branched nano-sheets and nano-wires on gold coated silicon substrates.

Researchers have also used CVD to coat the fibres of fabrics. One group generated superhydrophobicity with a coating of carbon nano-tubes on a carbon fibre fabric. Another, used range of natural and synthetic fibre fabrics and silicon compounds. They investigated in greater depth the commercially relevant poly ethylene terephthalate (PET) fabric and found 'unparalleled long-term water resistance and stability of the superhydrophobic effect' (Latthe, Gurav, Maruti, & Vhatkar, 2012). The fabric remained 'completely dry' and super-hydrophobic after two months of immersion in water, and continuous rubbing with a skin-like synthetic material under a significant load. Additionally, characteristics of particular relevance to the textile industry, namely tensile strength, colour and feel, were unaffected by the coating.

The sol-gel process is used industrially to produce a wide range of solid substances from solution (sol) via a gel-like colloidal state. Owing to the ease with which the colloidal system can be manipulated, a wide range of solid forms can be made this way, including thin films, fibres, aerogels, membranes, coatings and powders. Super-hydrophobic cotton, wool and polyester fabrics can be made by dispersing silica nanoparticles through the sol-gel matrix before applying it as a coating.

#### Surface morphology

Nano-scale morphology varies by synthetic route. Common morphologies include adsorbed particles (that largely remain distinct after the adsorption), rod arrays, pores, recesses, flower-like structures and sheets. In many cases, however, the surface is simply said to be 'roughened' without reference to any specific morphology.

#### Commercial potential

Many of the routes that have proved successful at laboratory scale, have features that make them unsuitable for industrial scale up (Xue, Jia, Zhang, & Ma, 2010). Such features include:

- Multi-step procedures
- Harsh reaction conditions
- Specialised reagents or equipment

Furthermore, little data is available on the durability and robustness of the surfaces produced and their super-hydrophobicity. Ensuring adequate durability of the super-hydrophobicity in particular remains a key challenge (Latthe, Gurav, Maruti, & Vhatkar, 2012).

#### **Paints and coatings**

Paints and coatings designed to create super-hydrophobic surfaces have been widely investigated (see 'Nanoparticles in paints and coatings'). Anti-graffiti paints that resist spray paint would be an example.

#### **Nanofibres**

Polymer fibres with nano-scale diameters can be extruded by electrospinning. Such fibres can be woven into super-hydrophobic or solvent resistant membranes or mats. Alternatively, they can be combined with silicon wafers to produce rigid super-hydrophobic surfaces.

#### Super-hydrophobic textiles

Nano-textured super-hydrophobic textiles have the potential to offer many benefits over traditional waterproof textiles. By definition, they should be more effective at repelling water. But they should also prove significantly more breathable than textiles rendered waterproof by traditional coatings based on rubbers, polymers or other wet chemical systems. This would be because the nano-scale surface structures would not substantively alter the porosity of the underlying fabric. How such textiles would compare with the membrane-based waterproof fabrics that have replaced coating-based equivalents for many products, and already offer considerably better breathability, is unclear.

There are good reasons to think that products made of nano-textured super-hydrophobic textiles could be packed up more quickly following contact with water than their traditional counter-parts. This is because of the way that such fabrics readily shed water: the beads of water roll off the surface.

For many textile products, the other phenomena that can be generated by the nano-texture could be as important as, if not more important, than the super-hydrophobicity. Indeed, the marketing for products that are already commercially available has focused on stain resistant properties, which roughly equate to omni-phobicity.

Durability remains a key concern. Normal wear and tear reduces the super-hydrophobic effect as fibres rub against skin, all manner of external materials and each other, and become smoother. As such, super-hydrophobicity must last long enough to meet consumer expectations. Durability may also be important in relation to the fragments of the surface released. A surface that deteriorates faster may release harmful nanoparticles at a faster rate and therefore present a greater risk to human health and the environment.

The other key concern is scale up, both in terms of technical challenges and cost.

#### Self-cleaning glass

Self-cleaning glass could be particularly useful for:

- Sensors designed for locations that would make manual cleaning difficult or impossible
- Architectural glass products (windows) and roof tiles
- Vehicular windows

Researchers have made transparent, flexible, self-cleaning surfaces from polydimethylsiloxane (PDMS) patterned with nano-scale cylindrical structures. Such surfaces could be used in solar cells to improve their efficiency, which is reduced by the build-up of dirt, particularly atmospheric dust, through normal use (Park, Im, & Choi, 2011).

### 4.6.3 Porous nanoparticles for drug delivery

Ensuring drugs reach their biological targets is a key challenge in healthcare. The active compounds may for example degrade on their journeys or fail to cross key biological barriers.

The pharmaceutical industry is interested in porous nanoparticles as potential drug carriers. The active compounds could be protected from degradation inside the pores. Additionally, the surface chemistry of the nanoparticles could be altered (the surfaces could be functionalised) to enable ready transfer across biological barriers.

# 4.6.4 Nanoparticles in paints and coatings

#### For biocidal activity

Micro-organisms (algae, lichen, fungi) can damage building facades. To mitigate this, the construction industry uses paints and coatings containing biocidal substances. Nanoparticles of a range of substances can be used, and compared with conventional equivalents, nanoparticles can be fixed more effectively in the coating matrix, reducing the risk of leaching (Kaiser, Zuin, & Wick, 2013). Additionally, incorporating nanoparticles into paints and coatings can improve the products in other ways by, for example, making them more resistant to scratching, more durable or better able to repel water. According to Kaiser *et al*, 'the paint and lacquer industry may become one of the largest users of nanomaterials in the near future'.

The nanoparticles can be of:

- Silver
- Titanium dioxide
- Copper
- Zinc oxide (with surface modification)
- Silica

The anti-microbial properties of silver are well known. As a precious metal, however, it is relatively expensive, and ultimately this may limit the applications for paints and coatings containing silver nanoparticles. Copper is cheaper, perhaps making it a more attractive option.

Titanium dioxide is cheaper still. Additionally, it has for decades been used as a paint pigment, and as such the paints and coatings industry is to some extent familiar with it. As well as making the paint or coating anti-microbial, titanium dioxide nanoparticles can:

- Improve the rheological properties
- Improve the mechanical properties
- Make it self-cleaning
- Make it photocatalytic
- Make it super-hydrophobic

The research community has investigated the photocatalytic potential of titanium dioxide nanoparticles in paints and coatings and found that, with indoor light, it is sufficient to crack volatile organic compounds, such as the fragrances commonly found in cleaning products, air fresheners and household solvents. Photocatalytic transformation of such compounds might be beneficial for human health.

Silica particles are widely used for wood preservation. They are also added to paints to make them scratch-resistant, protect from corrosion and give a high gloss finish.

Research on the potential risks to human health and the environment associated with nanoparticles in paints and coatings continues. The outcomes of such research may impact upon the development of commercially viable products.

#### As fillers

Manufacturers mix fillers into a wide range of materials. A filler might be mixed in primarily to substitute for a more expensive substance or group of substances, thereby reducing the cost of production. Alternatively, it might be included to improve the properties of the material.

Nanoparticles can be used as fillers for paints and coatings. Nanoparticles (aluminium, silver, copper, zinc oxide, aluminium oxide, titanium dioxide) can make paints more resistant to scratching, abrasion and erosion (Kotnarowska, Przerwa, & Szumiata, 2014) (10.5539/jmsr.v3n2p52). Carbon nanotubes can perform the same role.

The inclusion of silica or alumina nanoparticles in epoxy polyurethane coatings improves resistance to erosive wear by making the coatings harder, making the surface of the coatings smoother and filling pores in the coating that suppress crack formation.

# 4.6.5 Nanomaterials for pharmaceutical applications

The pharmaceutical industry in involved with a wide range of nanomaterials, including:

- Nano-suspensions
- Nano-spheres
- Nano-tubes
- Nano-shells Nano-capsules
- Lipid nanoparticles
- Dendrimers

#### Nano-emulsions

An emulsion is a colloidal system comprising two or more immiscible liquids. When at least one of the dimensions of the colloidal structure is nano-scale, the emulsion can be thought of as a nano-emulsion (Shah, Bhalodia, & Shelat, 2010). Typically, however, such materials comprise nano-droplets of one liquid dispersed though another, usually oil-in-water or, to a less commonly, water-in-oil.

Such materials are under investigation in relation to potential diagnostic, therapeutic and cosmetic applications. They are easily produced in large quantities via a mechanical extrusion process that is available worldwide.

The main application of nano-emulsions is the preparation of drug nanoparticles using a polymerisable monomer as the disperse phase, whereby the droplets act as nanoreactors.

Another application under development is the use of nano-emulsions as formulations, for controlled drug delivery and targeting. The high surface area to volume ratio and free energy of the dispersed droplets make them effective transport agents. Additionally, nano-emulsions generally have better properties (creaming, flocculation, coalescence, and sedimentation) compared with maco-scale equivalents.

The research community is interested in nano-emulsions for application in personal care products as potential vehicles for controlled delivery of cosmetics and dispersion of active ingredients in particular skin layers.

There is also considerable interest in their:

- Anti-microbial potential, particularly in relation to bacteria
- Use in mucosal vaccines
- Potential as drug delivery vehicles in cancer therapy

The oil droplets in an oil-in-water nano-emulsion can solubilise lypophilic drug compounds and carry them through hydrophilic biological regions that might otherwise inaccessible to such compounds.

## 4.6.6 Quantum dots

Quantum dots are nanoparticles comprising single crystals of semi-conducting compounds, most commonly compounds of cadmium. The extreme surface area to volume ratios common to all nanoparticles, combined with semi-conducting, lead to unique optical and electronic properties in quantum dots owing to the quantum confinement effect. These properties make quantum dots useful in a wide range of applications.

**In LEDs:** Quantum dots can be used to make coloured LEDs – quantum dot LEDs (QLEDs) – with several advantages over other types of LED (Bera, Qian, Tseng, & Holloway, 2010). Those advantages are already being exploited commercially. QLED consumer products, including lamps and electronic displays, are available<sup>62</sup>. The manufacturers say that, compared to conventional equivalents, the lamps produce a warmer light that is more like the light of an incandescent bulb and the displays produce a wider range of colours.

In solar cells: Quantum dots can be used as energy harvesting components in solar cells. The wavelength of the light that a quantum dots will interact with varies according to the size of the dot. Thus, by mixing dots of different sizes, it is possible to produce solar cells that absorb light of many different wavelengths. Theoretical calculations suggest such solar cells could be more efficient than conventional equivalents through more complete absorption of visible light (Zhang, Uchaker, Candelariaa, & Cao, 2013).

### 4.6.7 Sustainable nanomaterials

The research community has begun to consider the sustainability of nanoparticle production and application (Murphy, 2008). Production processes might be considered more sustainable if they:

- Use lower quantities of toxic pre-cursors (or make such pre-cursors redundant)
- Use water as a solvent where possible
- Use fewer reagents

- Use fewer synthetic steps

- Result in lower quantities of by-products and wastes
- Use ambient reaction conditions.

The sustainability of nanoparticle production and application is important in terms of industrial scale up because, in general, more sustainable processes are cheaper to run.

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<sup>62</sup> http://www.qdvision.com; http://nano.gov/sites/default/files/energy - coe-sullivan.pdf



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