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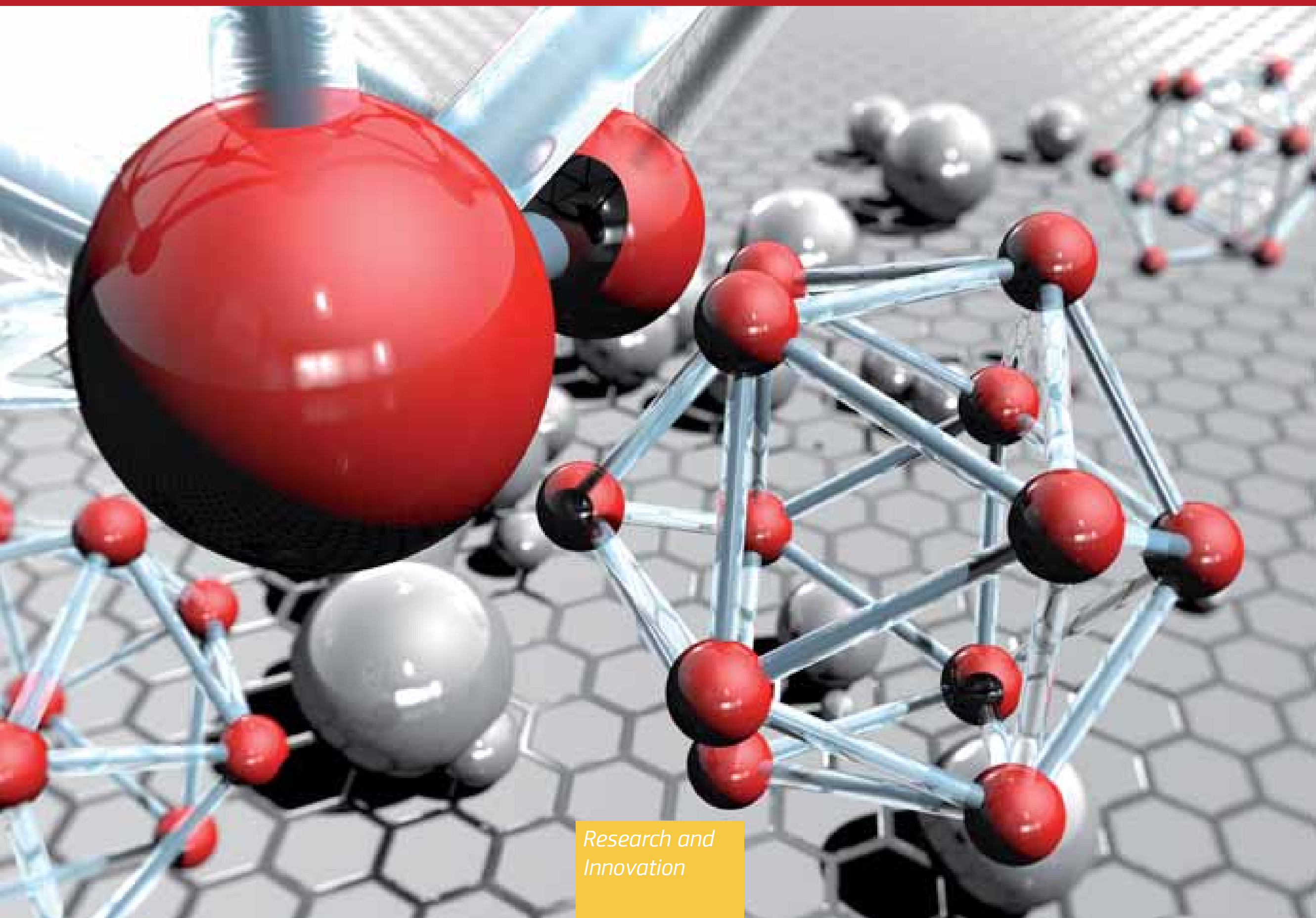
Nanotechnology:

the invisible giant tackling Europe's future challenges



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Nanotechnology: the invisible giant tackling Europe's future challenges

"What I cannot create, I do not understand"

Richard Feynman, 1959

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1. INTRODUCTION

1.1. How nanotechnology will help Europe make everything better

There is not just room at the bottom but *plenty* of room, said US physicist Richard Feynman in his now-famous 1959 lecture of the same title at California Institute of Technology[1]. Nanotechnology can not only create materials and devices on a minuscule scale 80 000 times smaller than a single human hair, but those technologies are likely to become all-pervasive, touching every aspect of human existence from medicine to energy generation.

What is so unique about the nanoscale? At this dimension, materials start to behave in ways different to their bulk counterparts. It also marks a crucial crossroads: the scale where artificial systems can interact with molecules and biological systems. A water molecule is just a little smaller than a nanometre (10^{-9} m); basic functional biological units like proteins operate on the nanoscale, while basic living entities like cells are 10-100 µm (where 1 µm or micron = 1×10^{-6} m) and bacteria 0.5-20 µm in size.

Nanotechnology will present new opportunities to make the stuff of life – electronics, medicines, everyday products and even our cars and homes – better, more cheaply and using fewer raw materials. Fitting neatly with the European Union's (EU) 2020 agenda for smart, sustainable and responsible growth, nanotechnology will help address key societal challenges facing the region, such as the medical needs of an ageing population, more efficient use of resources, developing renewable energy to meet the EU's 2020 commitments on energy efficiency, carbon emissions reduction and climate change. By confronting these challenges head on through technological innovation, nanotechnology will also bring much-needed economic growth and employment opportunities to the EU.

The European Commission (EC) has explicitly included nanotechnology as a theme in its research funding programmes over the past decade and supported nanoscientists through the European Research Council (ERC). But the current funding regime, the Seventh Framework Programme (FP7), will draw to a close at the end of 2013 to be superseded by a new funding initiative, Horizon 2020, which will run over the next seven-year period. Horizon 2020 promises to capitalise on the research foundations laid by FP6/7 and move into a new phase, where Europe's intellectual capital is turned into commercial technologies. The new regime promises to address a widely perceived shortfall in technology transfer and put Europe in a strong position to grasp new opportunities in the commercialisation of emerging nanotechnologies across a vast array of different sectors. This transition marks an appropriate moment to take stock of the achievements of the EU's nano-related research effort and look ahead to the coming years when the most promising technologies will start to emerge and consolidate.

1. *Richard P. Feynman,* Plenty of Room at the Bottom *(December 1959), www.its.caltech.edu/~feynman/plenty.html*

1.2. The invisible giant: a future enabled by nanotechnology

So what could a nano-enabled future look like? Feynman was right in his prediction that the room-sized computers of the 1950s would be miniaturised to a single, hand-held device, but could he have had an inkling of the transformation that smart devices from mobile phones to tablet computers have wrought on modern life? Ultimately, every industry that involves manufactured items will be impacted by nanotechnology. As Aidan Quinn, who heads the nanotechnology group at the Tyndall National Institute, University College Cork says: "Nanotechnology will play a key role in developing cheaper or better performing electronic devices, sensors and solar cells than those available now."

Let us take a brief trip through a typical day sometime in the future to get a snapshot of just some of the ways in which nanotechnology may be able to impact on our lives.

One of the spheres where nanotechnology is likely to have a significant impact is in better targeted, more effective and personalised healthcare. So how are you feeling today? In the future, this might be a question that can be answered with a simple blood or breath test able to track blood sugar levels for diabetics or detect the first signs of a host of common cancers. Smart sensing devices will relay test results automatically to medical practitioners, or specialists, prompting further action or consultation where necessary. Treatment could be targeted to individual requirements, thanks to cheaper and more accurate DNA sequencing using nanopore-based devices. Those treatments will also have far fewer side effects because nanoscale drug delivery systems take medication direct to diseased or damaged tissue. As well as more effective chemotherapies for cancer with less severe systemic side effects, these advances will also enable controlled delivery of insulin without injections and improved treatments for dementia.

Meanwhile, physical injuries will be treatable with a new generation of MRSA-resistant, anti-bacterial bandages ensuring quicker healing. More major injuries, to the spine for example, will now be more treatable with new approaches that encourage the body's own repair mechanisms to grow replacement tissue. Artificial bone, skin, or even cardiac tissue might also be grown to order to facilitate recovery from damage or disease or restore lost sight and hearing.

Even the clothes we wear may have become smarter and better thanks to nanotechnology. Embedded sensors could monitor vital signs, while built-in energy harvesters could power personal electronic devices. New flame retardant materials, meanwhile, promise improved protection for emergency services or military personnel operating in extreme conditions and self-cleaning, water-resistant materials could mean better raincoats or anti-stain clothing for all consumers.

Nanotechnology could find its way into every corner of our homes, too. The plethora of plastic items used on a daily basis could in the future be made from plant-derived raw materials instead of petrochemicals thanks to a new generation of nanocatalysts facilitating more efficient and sustainable industrial processes. Food packaging could feature RFID (radio frequency identification) tags indicating the freshness and safety of food. And even the water we drink may have been filtered through a new generation of nanoscale membranes to remove chemical residues, bacteria, pathogens and other impurities.

Turn on the light and that could also be thanks to nanotechnology. The electricity powering the highly efficient LED (light-emitting diode) lamps now standard in our homes is likely to have come from photovoltaic tiles or panels on the roof or from a larger solar array further afield relayed along a new generation high-capacity, low-loss cables made from carbon nanotubes. Distributed local energy sources will be supplemented by on- and offshore wind farms featuring a new generation of highly efficient, long-lasting turbine blades relying on nanomaterial coatings for their high performance.

Homes, offices and public buildings will offer a comfortable environment year-round with much lower running costs thanks to highly insulating nanomaterials, thermochromic windows, or even energy-generating façades. Every watt of power that comes into a building will be monitored by networks of smart sensors transmitting information wirelessly to energy management systems ensuring that it is used efficiently with little or no wastage.

Some of that on-site generated energy might also be powering hybrid or all-electric cars, featuring a new generation of nanomaterial-based long-range, compact lithium-ion batteries. Or perhaps, further into the future, a hydrogen economy will have been established where cars run, much as they did once on gasoline, on ultraclean hydrogen fuel. Nanoporous materials will provide on-board hydrogen storage, while nanocomposite materials will make cars lighter and more economical to run. Nanoadditives to paints and windows will ensure scratch-, UV- and dirt-resistance, while nanoparticle-based lubricants keep the engine running smoothly.

Thanks to nanotechnology, of course, computers will now deliver more computing power but require less energy. Integrating new nanomaterials and nanoprocesses, like the self-assembly of cheaply-produced chemically synthesized building blocks, with existing silicon-based systems will bring new functionality at lower costs. Super flexible screens for displays or e-readers will be printed cheaply and easily using organic materials. And we may even be moving into an era of quantum computing.

Meanwhile, traditional heavy industries will have been transformed, replaced by new nano-enabled processes that use less energy, consume fewer raw materials, are easier on the environment and create products that can be more readily recycled. As well as transforming sectors like papermaking or composites, a new sector producing nanomaterials in novel, perhaps bio-inspired, ways will have been established.

While nanotechnology promises less pollution and lower emissions, it will also enable a new generation of ultrasensitive sensing devices to monitor what pollutants are there. The sensing capabilities of nano-based techniques will also have a central role in defence and security technologies, in the detection of pathogen or chemical contamination, authentication to tackle counterfeiting, crime prevention and forensics.

But as with any novel technology, the public will want to be reassured and informed of the safety of new products, while workers producing these items require safe working conditions. These issues are being addressed, with nanotechnology standing as an example of one of the first emergent technologies to attempt to enshrine consideration of health, safety and environmental impacts from the very beginning.

Is there any aspect of modern existence that nanotechnology will not touch? But that all-pervasiveness will not appear intrusive. Nanotechnology promises to transform current technologies invisibly, making them smarter, more efficient and less costly to the environment.

1.3. Keeping up with the competition: global nanotechnology funding

Given the broad-reaching potential of nanotechnology, there has been a commensurate explosion in global research and development funding in recent decades. According to estimates, governments around the world have invested over USD 67 billion in nanotechnology research since 2000 and by 2015 investment, including that from corporate and private sources, could reach USD 0.25 trillion[2].

Europe's funding levels are largely comparable to its major competitors, the US and Japan, standing at EUR 6-7 billion in 2007/8. The EC is currently nearing the end of its largest ever research funding initiative, FP7, with a total of EUR 50.5 billion available during 2007-2013 to support projects boosting the region's competitiveness and tackling the grand challenges facing society in human health, climate change, energy and the environment.

Under FP7, the largest single share of funding for nanotechnology, some EUR 896 million for the period 2007-2011, comes through the dedicated Nanosciences, Nanotechnologies, Materials and new Production Technologies (NMP) stream, but significant support also comes through the Information and Communication Technology (ICT) stream (EUR 316 million), as well as the Health (EUR 74 million), Energy (EUR 55 million) and biotechnology (KBBE) streams (EUR 39.5 million). Meanwhile, the funding mechanisms that support individual researchers also serve as a conduit for nanotechnology-related funds, with the European Research Council (ERC) accounting for an estimated EUR 514.5 million and Marie Curie fellowships a further EUR 295 million.

Programme /Themes	Number of Projects	Funding in € million
ERC	296	514,5
Health	18	74,0
Energy	19	55,0
Environment	3	10,5
Food, Agriculture & Fisheries, & Biotechnology	13	39,5
NMP	238	896,0
Joint programmes	32	112,0
ICT	102	316,0
Security	4	10,2
Aeronautics	5	44,0
SPACE	9	24,3
Sustainable Surface Transport	3	7,0
SME	35	41,6
Science in Society	14	15,0
EraNets	4	10,5
Infrastructure	16	60,0
Marie Curie Actions	560	295,0
Regions	19	28,7
International Cooperation	10	6,3
TOTAL	**1400**	**2560,0**

FP7 Funding of Nanoscience-Nanotechnologies between 2007 and 2011 (source EC: Common Research Data Warehouse (CORDA))

2. *2011 Cientifica Report: www.cientifica.com*

1.4. The EU approach: integrated, safe and responsible

Although engineered nanomaterials and nanoscale processes look set to bring great benefits, there are major gaps in the scientific knowledge regarding potential adverse effects on human health and the environment. As an emerging technology that is likely to permeate all aspects of society and the economy, scientists and policymakers now have the opportunity to engage in a discourse on the potential benefits and pitfalls of nanotechnology in a considered and discursive manner with society at large.

The EU research enterprise is embracing this approach and has, since 2004, pledged to take an "integrated, safe and responsible" approach to nanotechnology. With dedicated funding streams supporting nanotoxicological efforts and activities exploring ethical aspects of nanotechnology, the consideration of potential adverse effects on human health and the environment is being embedded into the scientific and technological research enterprise. The outcomes of this anticipatory approach of assessing both the benefits and risks of nanotechnology will be fed into wider regulatory efforts at the European level. Sharing information, communication with the public, and fostering societal debate on nanotechnology are key supporting cornerstones of the Commission's research programme.

2. NANOTECHNOLOGY RESEARCH IN EUROPE

2.1. New science bringing innovation to the region

The strength of nanotechnology lies in the bringing together of disparate areas of science to create new knowledge and expertise that is greater than the sum of its parts. The European research enterprise aims to facilitate that interaction between disciplines, as well as between academia and industry to realise technological innovation.

The current programme, FP7, organises its support mechanisms via thematic clusters, highlighting key areas of societal need – human health, energy and the environment, and ICT – for particular emphasis. The following sections will discuss in turn the main sectors where nanotechnology is enabling significant progress and highlight a selection of exemplary projects that are representative of the major research themes.

2.2. A digital revolution: Nanoelectronics

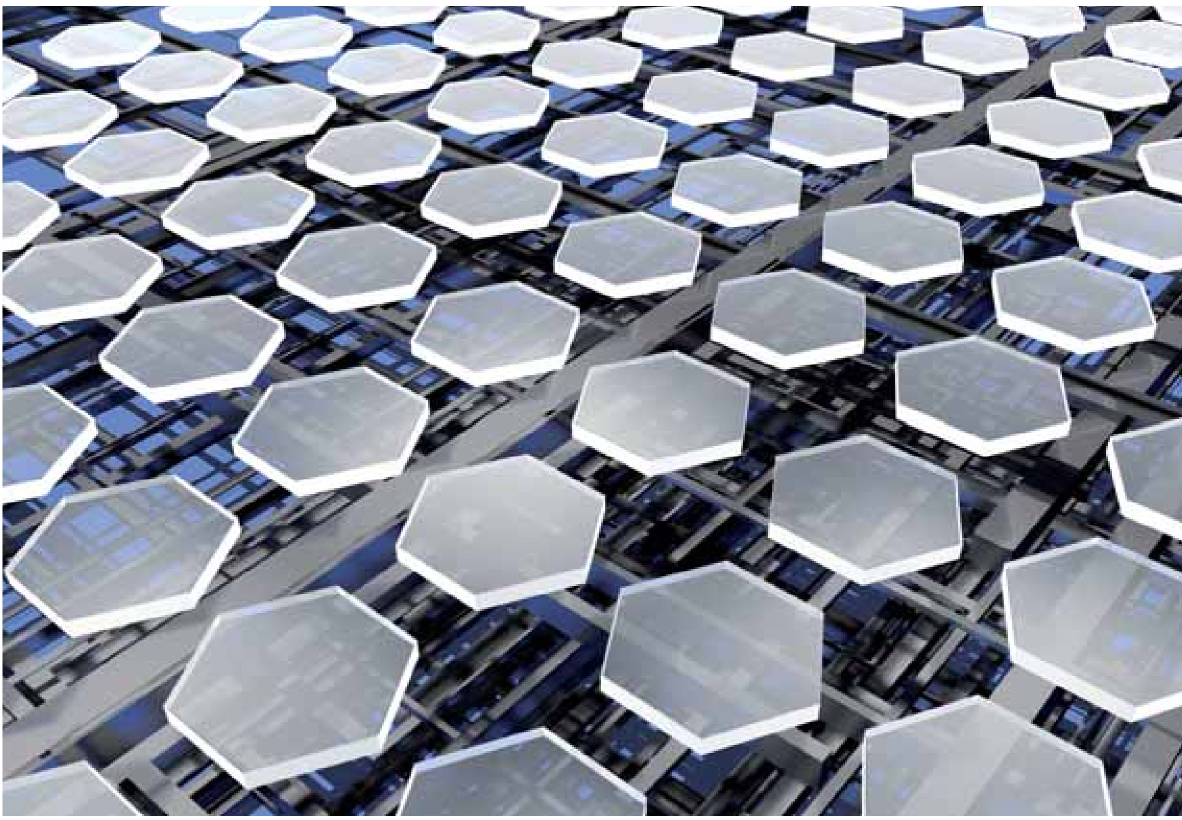
Digital technologies have revolutionised modern life in untold ways, but future improvements in speed and efficiency will rely on a new generation of nanoscale materials like nanoparticles, carbon nanotubes and quantum dots. Over the last fifty years, semiconducting materials – primarily silicon – have enabled a revolution in ICT. In 1965, at the dawn of this new age, Intel co-founder Gordon E. Moore predicted that improved computing power would be delivered by a systematic shrinking the size of transistors in integrated circuits (ICs). 'Moore's law', as it is known, has held true ever since but is now approaching a physical barrier, beyond which it is no longer possible to shrink the dimensions of transistors and other IC components. Moving beyond the confines of complementary metal-oxide-semiconductor (CMOS) technology within the next 10-15 years will take the industry into a strange and unpredictable world of interatomic interactions and quantum mechanical properties, requiring disruptive new technologies. This new regime is likely to rely on existing semiconductor electronics combined with molecular materials, nanoparticles, nanotubes and nanowires, quantum dots and graphene – single sheets of carbon atoms arranged in a honeycomb lattice. Ultimately, pure molecular electronics or quantum devices may take over in some applications.

Going beyond CMOS: GRAND

As the semiconductor industry looks for material solutions to enable the continued downsizing of chip components, graphene is emerging as a prime candidate.

This EUR 3.2 million FP7 ICT project is taking the first steps, assessing graphene nanoribbons for CMOS processing and on-chip integration.

www.grand-project.eu/



Small and cool: NANOHEX

Heating is a problem at the macroscale too for high-tech industries reliant on large-scale computing. It can take as much energy to cool as it does to run a data centre.

But nanotechnology can help. A new liquid coolant using engineered nanoparticles, which could be up to 40% more efficient than conventional coolants, is being developed as part of a EUR 8.3 million FP7 NMP project.

"Traditional cooling systems using air or water are not always efficient [and] can be expensive," says Mamoun Muhammed of the Royal Institute of Technology Sweden. "Nanofluids could help provide a more economic and efficient cooling system."

www.nanohex.org/the-project

The main thrust of EU-funded projects in this area is tackling the technological challenges as feature sizes in switches, memory cells, chip-level interconnects and transistors continue to shrink. The semiconductor industry carefully plans its transitions to smaller scales, moving step-by-step to specific feature sizes known as 'nodes'. Research efforts are focused on upcoming nodes, such as the 22 nm node, as well as 'unconventional' solutions beyond the limits of current CMOS technology.

Initially, efforts are looking to improve CMOS technology using novel semiconducting materials with advantages over silicon such as germanium and III-V compound semiconductors[3]. But silicon, in the form of nanowires thousands of times smaller than the diameter of a human hair, could continue to be the material of choice for transistors. In the move to sub-22 nm nodes, interest is turning to novel carbon materials such as nanotubes, molecular wires and graphene, whose novel electronic properties have already made it a prime candidate for beyond-CMOS switches and interconnects with feature sizes down to just 5 nm[4].

Interconnects, which link together devices on a chip, are crucial to operating speed. Historically, interconnects were fabricated from aluminium, but as the number of transistors has increased, wiring has switched to copper. But with the density of interconnects increasing still further, new options are required. Carbon nanotubes are among the most promising alternatives under investigation that could be cost effective and easy to implement on an industrial scale[5]. They could also help solve one of the other major issues facing chip designers, local heating from the close proximity of many individual devices[6]. Future devices will need to dissipate heat better and employ ultra-low power transistors[7].

Computer memory, which comes in two forms – primary or volatile memory (RAM, DRAM, cache) for providing information fast and secondary or non-volatile memory

Building electronics from the bottom-up: FUNMOL

Metal or semiconductor nanoparticles and functional organic molecules 10 000 times smaller than a human hair could form the basis of future electronic and sensing devices. This EUR 3.5 million FP7 NMP project explored the integration of 'bottom-up' methods, where Lego-like nanoscale atomic and molecular building blocks are assembled into structures, with conventional 'top-down' devices fabricated on silicon chips.

Integrating novel nanomaterials and processes with existing top-down technologies is opening up new directions in printable transparent electrodes for light-sensitive photodectectors and, further down the line, in low-cost, point-of-care diagnostics like pregnancy tests.

"The interface between existing systems and new nanomaterials and processes is where key opportunities are," says Aidan Quinn, Tyndall National Institute, University College Cork, Ireland. "Nano can make it better or cheaper."

www.funmol.eu/

3. *EU project* DUALLOGIC *(www.ims.demokritos.gr/DUALLOGIC/).*
4. *EU projects* CONCEPTGRAPHENE *(www.chalmers.se/hosted/concept-graphene-en/) and* GRENADA *(www.fp7grenada.eu/).*
5. *EU project* VIACARBON.
6. *EU project* NANOPACK *(www.nanopack.org/).*
7. *EU project* SMARTGATE *(www.smartgate-erc.eu/).*

(ROM, flash, magnetic storage, hard and optical disks) for program and data storage, will require new magnetic materials. Regardless of type, all memory devices store information as a binary code using tiny magnetic grains, which can be either magnetised (denoting '1') or unmagnetised (0). Each storage unit or 'bit' comprises around 100-600 grains, which are now typically just 10 nm in size. Going smaller than this will make it increasingly difficult if not impossible to separate signals from noise, so new data storage concepts are needed. One promising option is spintronics, where the 'up' or 'down' spin of an electron is used to store information instead[8]. Graphene and single-walled carbon nanotubes are compelling candidates for such spintronic devices[9], as are magnetic nanowires, which could take memory into three-dimensions to provide ultra-high density information storage[10].

Despite myriad advantages, current silicon-based electronic fabrication methods are expensive, energy-intensive and time-consuming. But the integration of new materials and processes could change that. Organic materials, for example, could enable roll-to-roll manufacturing of flexible electronic and photonic devices, with the commensurate benefits in lower production costs and novel applications[11]. Flexible, transparent organic electronics could provide low power displays for e-readers or electronic newspapers, as well as RFID tags and easy-to-use sensors for health and environmental monitoring. Organic solar cells, meanwhile, could harvest light at lower levels earlier in the day and for the more of the year, as well as be integrated into a variety of devices and objects from windows or building facades all the way through to clothing that could recharge small electronic items.

Meanwhile, nanoscale materials also herald a new generation of ultra-sensitive, reliable and easy-to-use sensors for healthcare and environmental monitoring. Graphene, for example, could be ideal for highly responsive and durable gas sensors detecting toxic pollutants such as carbon monoxide and dioxide, hydrogen sulphide and ethanol even in very low concentrations[12]. Tiny precision-fabricated machines, known as micro- and nano-electromechanical systems (MEMS, NEMS), could also provide a route to low-cost and low-power sensors for a range of mass-market applications[13], as well as environmental monitoring and biological sensing[14]. This kind of physical sensor features a suspended beam as small as a nanowire, which vibrates at a particular frequency. When a target gas molecule, DNA or protein lands on the sensor, the mass of the vibrating wire is altered, producing a change in signal that can be detected.

High temperature sensing on the boil: SOI-HITS

Silicon-on-insulator sensors could help reduce energy wastage in domestic boilers, oil and gas storage and transportation, and CO_2 capture and storage.

This EUR 3 million FP7 ICT project aims to cut the energy consumption of a domestic boiler by 15%, saving European consumers up to EUR 3.6 billion a year.

www.soi-hits.eu/

But the reach of nanoelectronic materials does not end here. Novel nanomaterials and architectures could yield tiny lithium-ion batteries for microelectronic devices and biomedical micro-machines[15], lighter more flexible overhead power transmission lines[16], more affordable and efficient solid-state LEDs[17] or even a bridge to the biological world, providing implantable devices able to control neuronal signaling and help in the treatment of spinal cord lesions or neurodegenerative diseases[18].

8. *EU project* 3SPIN.
9. *EU project* SYLO.
10. *EU project* 3DMAGNANOW.
11. *EU project* ONE-P *(www.one-p.eu/)*.
12. *EU project* GRAPHENEGASSENSORS.
13. *EU project* NIRVANA *(www.nirvana-fp7.eu/)*.
14. *EU project* NEMSIC *(www.nemsic.org/)*.
15. *EU project* SUPERLION.
16. *EU project* HPCNTW.
17. *EU project* SMASH.
18. *EU project* CARBONANOBRIDGE.

2.3. Guiding light: Nanophotonics

Nanomaterials can be used not only to manipulate electrons, but also single photons of light. This ability is nothing new. The human race has been harnessing the unusual optical properties of nanomaterials for more than a thousand years with one of the most famous examples, the Lycurgus cup, on show in the British Museum in London. Fourth-century glassmakers in Rome used gold and silver nanoparticles to turn the opaque green cup a translucent red when held up to the light.

New and exquisite control of nanoparticles, however, could yield an improved generation of lasers (see textbox, left), light sources, optical fibres and detectors. Gold is still particularly valued because it works well in visible and near infrared light, ideal for improving photovoltaics, displays, and as part of sensing and detection devices[19] for medicine, biological research (see textbox, below) and environmental monitoring.

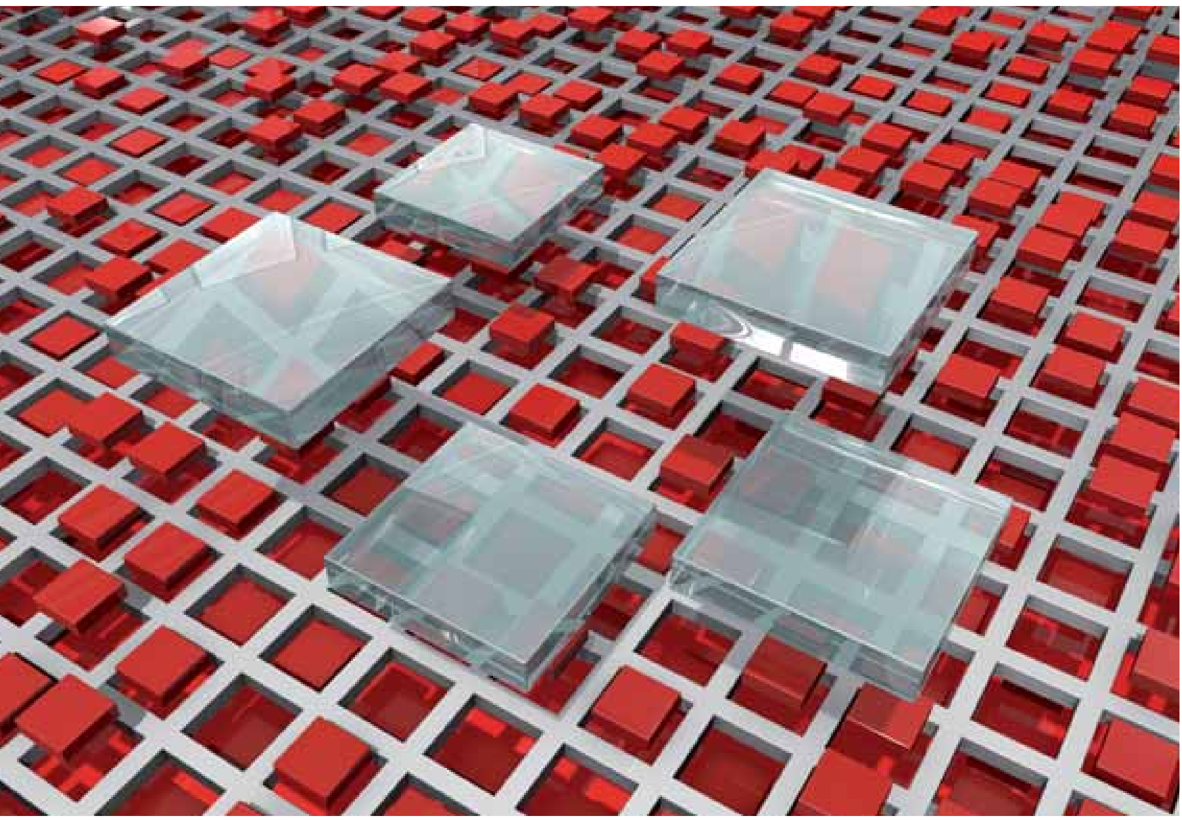
Ultrafast lasers on the dot: FAST-DOT

Lasers for biomedical applications like imaging and cell-surgery are typically expensive, bulky and hard to use. A new generation of low-cost, reliable and highly efficient ultra-short pulse broadband lasers could be made possible by using novel semiconductor nanostructure clusters.

Thanks to the EUR 14.75 million FP7 ICT project led by the University of Dundee, these high-performance semiconductor quantum dots are now being implemented in prototype devices for biophotonic applications.

http://fast-dot.eu/

19. *EU project* PHOTOSENS *(www.photosens.eu/).*



The ability of nanoparticles to collect light energy, like a tiny antenna, and transmit it to another material could have benefits for polymer solar cells. Although lower efficiency than their silicon-based counterparts, polymer solar cells could enable cheap, large-area systems on building windows, facades or roofs. Nanoantennas could also capture a broader swathe of the light spectrum, making solar cells less sensitive to the angle of incoming light.

Nanophotonics could also provide a solution to the problem of communication on and between computer chips. Just like the optical fibres that bring digital information to our homes at high speed, light could also relay information around computer chips more readily than an electrical signal. To achieve this, tiny optical interconnects will be needed in the form of self-assembled nanocrystals or nanowires, along with photonic crystals to guide light around sharp corners[20]. Using optical interconnects has the added advantage of consuming much less power[21].

But one of the more intriguing potential applications of nanophotonics lies in information processing. Because of the capacity to manipulate both electronics and photons, nanophotonic devices could serve as a basis for the massively parallel processing of high volumes of information such as from the Large Hadron Collider at CERN, for example, or radar data from traffic monitoring systems[22].

Shedding a new light on biological analysis: WIPFAB

Bringing together photonic materials with microfluidic lab-on-a-chip approaches could help deliver a new generation of point-of-care diagnostics for infections, cancer, heart disease and diabetes, as well monitors for air and water pollution.

The EUR 3 million WIPFAB FP7 IDEAS ERC project is contributing to that effort through the development of new optical waveguide material systems and nanostructured waveguide surfaces.

"If our materials and waveguide platform can be standardised and applied to a wide range of biochemical/biological analyses, the market could be vast," says principal investigator James S. Wilkinson of the University of Southampton

20. *EU project* FIREFLY *(www.fp7-firefly.eu/).*
21. *EU project* ULPPIC.
22. *EU project* NARESCO.

2.4. Where nanotechnology meets DNA: Nanobiotechnology

Where nanotechnology meets biology on the scale of proteins, DNA and cells, revolutionary scientific tools and new applications in nanomedicine and the self-assembly of materials are within reach. Here biological processes are being used in the short-term to inform nanomedicine and biotechnology, while longer-term efforts are mimicking nature to create nanoscale machines like molecular motors.

Nanobiotechnology is providing a wealth of new tools for biological research at the single molecule and cellular level. For example, nanoscale porous materials are being explored for DNA sequencing, with the potential for simpler and more accurate detection. Meanwhile, nanostructured materials can also give an insight into how bacteria interact with their physical surroundings[23]. In the longrun, a better understanding of the factors afecting bacterial growth could inform the development of much-needed new antibiotics (see textbox).

A more immediate and practical application is the prevention of bacterial build-up on surfaces (see textbox, below). Known as 'biofilms', these bacterial buildups can be extremely problematic in healthcare, where their presence on surgical implants or catheters can cause infection. But nanoscale coatings based on plastic-like polymers that release zinc, silver or copper ions during use have the potential to curtail bacterial attachment and prevent buildup.

23. *EU projects* NANOFORBIO *(see textbox) and NANOP.*

Putting the squeeze on cells: NANOFORBIO

Nanosized holes in membranes are being used to trap and detect DNA molecules as part of a EUR 2.5 million FP7 ERC IDEAS project led by Cees Dekker at Delft University of Technology. The approach could enable the detection of single proteins, which is crucial for the genomic screening of hereditary diseases.

Meanwhile, in a parallel effort, the project is exploring how bacteria respond to being squeezed by a nanostructured physical environment. The study is pushing the boundaries of basic science, but could ultimately yield a radically new approach to antibiotics, says Dekker.

Other efforts in nanobiotechnology remain firmly rooted in the present with solutions for intelligent, sustainable food packaging[28], membranes for filtering and purification, and devices for assessing food safety and quality. Making screening methods for foodstuffs quicker, easier, more reliable and cheaper could help avoid situations such as the recent UK scandal involving horsemeat. One EU project, for example, is using activated nanostructure sensors to develop monitoring systems able to detect pathogens, drug residues or fraudulent material in milk[29].

One of the more science fiction-like aims of this field is the development of molecular machines capable of carrying out complex tasks at the nanoscale. Research efforts are focusing on biomolecular motors[24] and DNA nanomachines based on interlinked ring structures called catenanes or dumbbell-shaped molecules known as rotaxanes[25]. Such tiny machines could carry out biosensing tasks, circuit assembly for nanoscale electronic devices or even act as artifical muscles. Meanwhile, taking inspiration from magnetotactic bacteria, researchers are creating magnetite nanoparticle-based nanorobots that can 'swim' in a magnetic field[26]. But friction can be a major problem at such a small scale, so researchers are turning to carbon nanotubes and graphene to get around this sticky problem[27].

Stopping bacteria getting a grip: EMBEK1

Nanostructured surfaces can stop bacteria taking a hold and multiplying.

"We are developing surface coatings for implants and dressing material on which the development of bacteria is hardly possible," explains researcher Renate Förch of the Max Planck Institute for Polymer Research in Germany, leader of a EUR 2.9 million FP7 NMP project.

These antimicrobial films could be applied to medical devices such as catheters, wound dressings and personal care items.

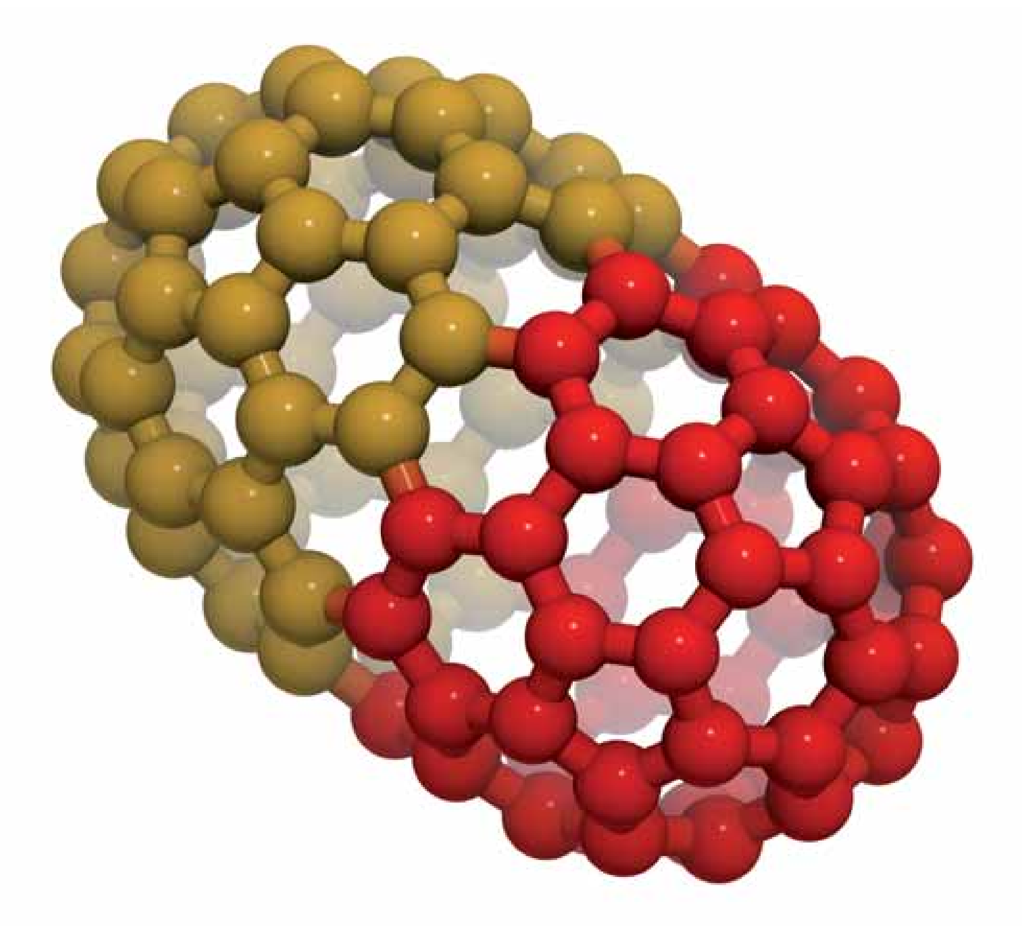
www2.mpip-mainz.mpg.de/eu-projekte/embek1/

24. *EU project* NANOTRANS.
25. *EU project* DNA MACHINES.
26. *EU project* MB2.
27. *EU project* CARBONNEMS.
28. *EU project* NANOBARRIER *(www.sintef.no/nanobarrier).*
29. *EU project* NANODETECT *(www.nanodetect.eu/).*

2.5. Detecting early and targeting treatment: Nanomedicine

Implementing advances in nanotechnology and biology in the medical and clinical arena will help Europe support its ageing population, which is putting an increasing burden on care networks and the economy. One in five of the current population is over 65, a proportion that is set to grow to one in four over the next two decades. The implications are startling: one in three of the population is likely to develop cancer, with currently over 3.2 million cases diagnosed and 1.7 million cancer-related deaths recorded every year in Europe alone. Nanotechnology could transform future cancer treatment, as well as that for a whole host of other chronic and debilitating conditions of old age including cardiovascular disease, rheumatoid and osteo-arthritis, and neurodegenerative disorders (Alzheimer's and Parkinson's), improving patient outcomes, reducing long-term social care costs and making healthcare more affordable.

Diagnosing cancer early is vital but is complicated by the fact that it is not one disease but over 200 different variants. Accurate diagnosis is, therefore, not only challenging for clinicians but also potentially lengthy and invasive for patients. Instead, what if a single breath could indicate the early stages of the most common cancers like lung, breast, colorectal and prostate? This is exactly what one EU-funded project is attempting using an array of highly-sensitive detectors based on gold nanoparticles to identify the biomarkers of cancer in breath (see textbox). Other efforts are harnessing the unique



A nose for cancer: DIAG-CANCER

A single breath could reveal the telltale disease biomakers of early stage cancers, according to this EUR 1.2 million FP7 ERC IDEAS project.

Researchers are developing a nano artificial nose – or NA-NOSE – sensing device based on molecularly modified metallic nanoparticles able to detect the first signs of common cancers like lung, breast, colorectal, prostate, gastric, liver, ovarian and head-and-neck. Patients could ultimately benefit from more timely and effective interventions, improving survival and quality of life while reducing invasive procedures and hospitalisation.

The same approach could also diagnose the early stages of Parkinson's, Alzheimer's, kidney disease and multiple sclerosis.

Schematic of the NA-NOSE concept. (Credit: Hossam Haick, Technion-Israel Institute of Technology.)

Fig. 1 A schematic illustration of the NA-NSOE concept.

photoluminescent, magnetic and optical properties of nanomaterials to develop super-sensitive, high-throughput clinical, laboratory and point-of-care devices for testing body fluids or cancerous tissue[30].

Cancer-related deaths are often the result of metastases, where the original cancer cells have spread beyond the original tumour site, rather than the primary disease itself. So parallel projects are focusing on detecting these breakaway disease-bearing cells, known as circulating tumour cells or CTCs[31], to give clinicians a low-cost, minimally invasive insight into disease progression and patient response to treatment.

Neurodegenerative conditions or dementia, which affect well over 6 million sufferers in Europe with a further 1.4 million cases added each year, present a similar set of problems. Reliable diagnosis is complex and time-consuming, requiring both psychological testing and brain imaging. But tiny semiconducting quantum dots labelled with antibody biomarkers could provide a much earlier diagnosis via a simple blood test[32], an approach that could be less onerous for patients and more cost-effective for healthcare providers.

Once a basic diagnosis has been made, techniques like magnetic resonance imaging (MRI), X-ray computed tomography (CT) and positron emission tomography (PET) are commonly used to track the progress of disease and monitor the effects of treatment. Tiny magnetic particles of gadolinium are already in use as a contrast agent to improve the quality of information gathered by MRI scans. Taking this approach to the nanoscale could not only improve resolution – potentially down to the level of a single cell – but bring other advantages as well.

Using targeted agents to both identify diseased tissue and deliver pharmacologically active treatments triggered by light, heat or a magnetic field is a new approach known as 'theranostics'. The combination of existing, well-established techniques like MRI and ultrasound with engineered nanoscale delivery and monitoring agents is a very attractive option, which is being pursued as a joint priority area by the EU. One of the 25 or so projects in this effort is exploring the use of ultrasound to create localised pressure or high temperature at a disease site to trigger the release of drugs from nanocarriers (see textbox).

30. *EU project* NAMDIATREAM *(www.namdiatream.eu/).*
31. *EU project* RBCE-GENODIAGNOSENS.
32. *EU project* NANOGNOSTICS *(www.nanognostics.org/).*

Magnetic nanoparticles are also ideal carriers for tumour-targeting agents and anticancer drugs to transport treatment to precisely where it is needed. An external magnetic field can guide the particles into place and then induce local heating to unzip the agents or drugs[33]. Another novel approach being pursued is the use of super-fast laser pulses to initiate ablation of cancer cells via noble metal nanoparticles[34].

As far as the patient is concerned, targeted drug delivery promises less invasive treatment with minimised side effects. Particularly in cancer care, reducing the often severe side effects of chemotherapy would be a significant boon for patients, while also reducing unnecessary hospitalisations. The approach could also allow higher local doses to be administered, improving treatment outcomes without increasing side effects. Though straightforward in concept, the practice is demanding, requiring delivery entities that can hold different therapeutic agents, move across barriers like the blood-brain barrier (BBB), recognise a target, and deliver a cargo[35].

Triggering nanocarrier drug delivery: SONODRUGS

Imaging techniques MRI and ultrasound are being combined with specially engineered nanocarriers to deliver treatment directly to diseased tissue.

In this EUR 10.7 million FP7 NMP project, drug-loaded liposomes are attached to microbubbles and injected into the body. Ultrasound triggers the delivery of drugs, as well as local heating (hyperthermia), while MRI tracks the treatment process. The approach has been successfully tested for anticancer drug doxorubicin and RNA-based compounds for cardiovascular disease.

www.sonodrugs.eu/

An insight into diabetes: VIBRANT

This EUR 8 million FP7 NMP project is developing a polymer-based nanocontainer for carrying fluorescent quantum dots and superparamagnetic iron oxide nanoparticles to facilitate the better diagnosis of diabetes by MRI.

The nanocontainers are decorated with b-cell targeting molecules and could also deliver therapeutic agents to treat the condition as well.

www.fp7-vibrant.eu/

This revolutionary approach is also being taken to tackle another major health issue facing Europe – diabetes. There are currently 30 million diabetics across the region, but the number is expected to grow to around 50 million by 2025. As well as potentially devastating effects on patients – including cardiovascular disease, kidney failure, neuropathy, lower limb amputation and blindness – the condition costs European care providers some EUR 50 billion a year. One EU project is focusing on the cause of diabetes, the decline in insulin-producing b-cells, using MRI to diagnose and quantify the disease, as well as deliver therapies (see textbox above).

Nanoscale delivery agents could also enable drugs to reach parts of the body that would otherwise be difficult or impossible. For example, treating diseases like Alzheimer's and Parkinson's requires drug molecules to cross the BBB. The fine, thread-like nature of carbon nanotubes could be ideal for piercing the BBB to deliver drugs[36] or worming into tumour cells[37]. If nanoparticles could facilitate the transport of drugs to the brain, it could help address dementia, which affects some 24 million individuals worldwide.

Getting a head start on drug delivery: NAD

Getting a drug molecule across the blood brain barrier (BBB) to treat diseases like Alzheimer's and Parkinson's is challenging.

This EUR 10.9 million FP7 NMP project is developing nanoparticles that can deliver dementia treatments where most needed.

www.nadproject.eu/

33. *EU project* NANOPUZZLE.
34. *EU project* MINT *(www.elec.gla.ac.uk/mint/).*
35. *EU project* NANOTHER *(www.nanother.eu/).*
36. *EU projects* CNTBBB *and* NAD *(www.nadproject.eu/).*
37. *EU project* ANTICARB *(http://anticarb.org/).*

As well as delivering drugs, nanoparticles can also provide a means to attack tumours in novel ways. In an emerging approach known as hyperthermia, magnetic nanoparticles are used to induce local heating at the site of a tumour and destroy diseased tissue[38]. Nanoparticles are simply injected into the body and directed to the tumour site by an external magnetic field via MRI, for example, offering a much less invasive treatment for small, non-defined tumours than conventional surgical approaches.

Nanotechnology could also take medicine in another exciting new direction – assisting the body to repair itself. By bringing together smart nanoscale biomaterials and advanced cell therapy, the body's own self-repair mechanisms can be harnessed to mend, regenerate or replace damaged tissues or organs. Nanostructured or nanopatterned biomaterials serve as intelligent scaffolds that initiate, stimulate and direct the growth of new tissue into the required shape with the correct function.

Touching a nerve: I-ONE

In the future, nanotechnology could make it possible to regenerate injured nerve tissue.

Using flexible organic electronics, this EUR 3.8 million FP7 NMP project is developing implantable devices that encourage nerve tissue repair by providing local electric stimulation, while sensing and controlling the body's inflammatory response. As well as providing the right microenvironment for stem precursor cells to differentiate into neural cells, the system will also be able to deliver growth factors, neurotransmitters and other drugs to facilitate tissue growth and repair.

http://ione-fp7.eu/

Using nanotextured scaffolds or templates with the right cues, stem cells can be given a growth plan to regenerate tissue. EU research efforts are taking this approach to establish new classes of biomaterials that bridge the gap between the highly complex architecture of the human body and the cruder efforts offered by cell culture[39]. Other efforts are using nanopatterned scaffolds or surfaces to direct the growth of replacement cardiac tissues[40], bone and cartilage[41] and even skin[42].

Many tissue-related injuries have devastating consequences, particularly spinal cord injuries, which affect millions of people worldwide and are hard to treat. Nanofibres are being explored to direct and encapsulate neural stem cells transplanted into the spine to repair the damage and regenerate tissue[43], while neuronal networks are also being grown on nanopatterned surfaces[44]. Implantable devices, made out of biocompatible materials, are also under development to deliver local electrical stimuli to promote nerve regeration, sense inflammation and control the immune response (see textbox above).

Meanwhile, a better understanding of the physical operation of the body on the nanoscale, bringing together a whole host of disciplines from cognitive science to engineering to cell biology, is heralding a new generation of robotic devices, which will transform the lives of those with physical or visual disabilities. Using sensors based on nanoelectromechanical system (NEMS) arrays and hybrid bio-NEMS, one EU-backed project is developing a touch-sensitive robotic finger[45]. Not only could such a robotic system assist the disabled, it could also be used for space exploration, extreme environments or product testing. Nanostructured materials are also being used to make tactile screens to help the visually impaired read complex mathematical equations or graphical images[46].

38. *EU projects* NANO3T *(https://projects.imec.be/nano3t/) and* MULTIFUN *(www.multifun-project.eu/).*
39. *EU project* MASC.
40. *EU projects* NANOCARD *(www.mf.mpg.de/NanoCARD/) and* RECATABI *(www.recatabi.com/).*
41. *EU projects* OPHIS *and* INNOVABONE *(www.innovabone.eu/).*
42. *EU project* ARTIVASC 3D *(www.artivasc.eu/).*
43. *EU project* SCINSCEF.
44. *EU project* NANOSCALE *(www.nanoscale-fp7.eu/).*
45. *EU project* NANOBIOTOUCH *(http://nanobiotouch.org/).*
46. *EU project* NOMS *(www.noms-project.eu/).*

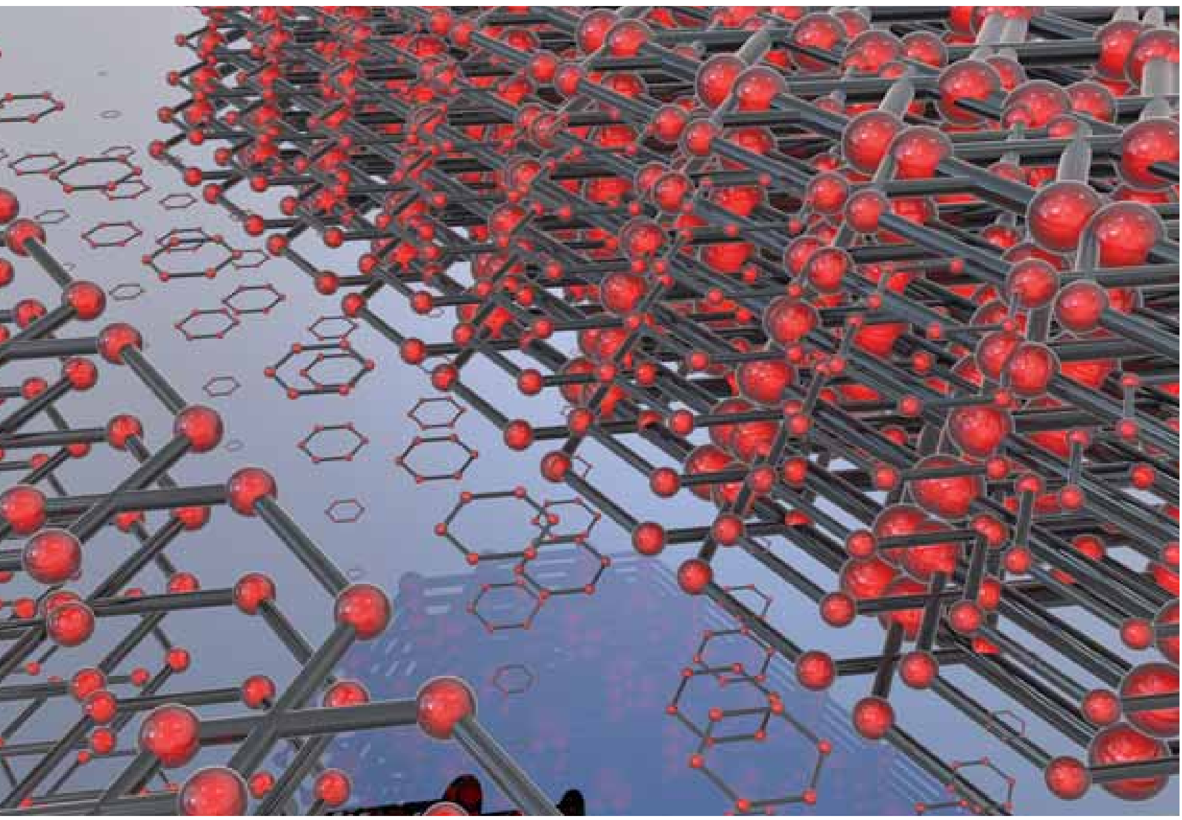
2.6. Building materials from the bottom-up: Self-assembly

The biological world is also inspiring scientists to look at new ways of assembling materials and structures using Lego-like molecular building blocks. This means of creating materials is known as directed- or self-assembly and could prove useful in diverse areas from nanomedicine, catalysts, nanoelectronics and nanophotonics to applications in energy and environmental monitoring.

The key to self-assembly is to find triggers that bring molecules together spontaneously to create larger structures. This almost-magical process of creating order from chaos is driven by complex chemical recognition and self-organization processes, which scientists are only starting to understand. In one effort, the focus is on 'programming' functional molecules to self-assemble into nanofibres or tubes that can be used in solar cells[47].

This approach could also provide a route towards the creation of artificial cells, bio-hybrid cells and bio-mimicking membranes[48]. Meanwhile, the same approach is being used to self-assemble target proteins over nanoporous substrates for drug screening[49].

47. *EU project* PROGRAM-NANO.
48. *EU project* NMU-LIPIDS.
49. *EU project* ASMENA *(www.asmena.ethz.ch/)*.



Self-assembling materials could even be printed using ink-jet technology and microfluidics[50]. Nano-patterned surfaces underpin the process, acting as templates to direct assembly into the desired pattern. This methodology demonstrates how top-down patterning and bottom-up assembly processes are being united into a single, effective fabrication technique.

A recipe for self-assembly: NANODIRECT

Just like any other assembly process, making materials at the nanoscale requires a toolbox. But this EUR 3.7 million FP7 NMP project is hoping to create a toolbox for nanomaterials that assemble themselves.

Using gold nanoparticles dispersed in a fluid, known as a nano-colloid, the assembly process is driven by electric and flow fields. By varying the shape of the gold nanoparticles and adding sticky ends, large arrays of particles – or superlattices – can be formed, the first step towards self-forming materials.

http://nanodirect.eu/NANODIRECT.html

50. *EU project* NANO3D.

2.7. Getting a better reaction: Catalysts

Underpinning modern life are many complex chemical reactions, from those that keep cars running smoothly to others that produce the myriad objects around us. Catalysts drive many of these reactions and even small improvements in performance can lead to significant savings in energy and raw material use. The large surface area of nanoporous materials and nanoparticles makes them ideal putative catalysts. But not only can nanoscale catalysts reduce the amount of raw materials used in the process, they can also reduce the amount of catalytic material needed too. Since many catalysts are based on precious metals like platinum and palladium, any reduction could become vital in the future as soaring usage in new applications like fuel cells puts pressure on limited stocks.

Meanwhile, progress in sustainable production and emerging technologies like carbon capture will also require new catalytic materials. EU-backed research efforts are exploring a wealth of different directions to deliver new catalyst materials including self-assembled, porous organic-

A holey new approach to catalysts: NANOMOF

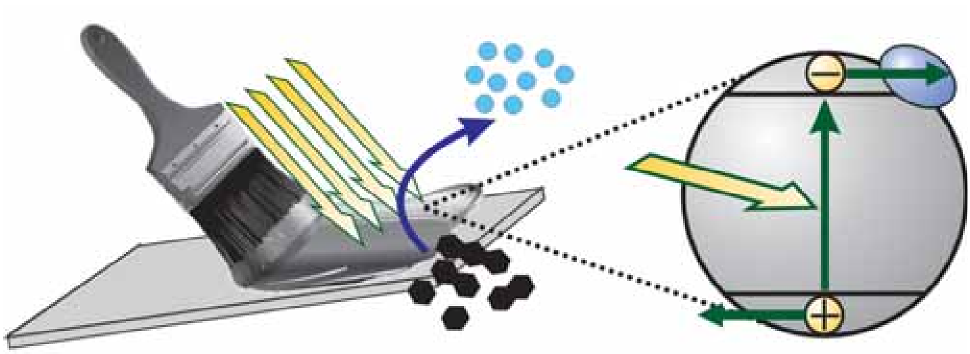
Nanoporous materials made from a mixture of inorganic and organic components – or metal-organic frameworks (MOFs) – could make exceptional catalysts.

The extraordinary properties of MOFs are being explored in this EUR 5.1 million FP7 NMP project as environmentally friendly and economical catalysts for the oleochemical industry, which produces chemicals from plant and animal fats. These sustainable compounds could replace petrochemicals in detergents and personal care products from toothpaste to shampoo.

www.nanomof-project.eu/

inorganic materials[51], low-cost ceramic and silicon carbide nanoparticle alternatives to precious metal automotive catalysts[52] and large organic molecules combined with nanoparticles[53]. Meanwhile, other efforts are focusing on promising gold nanostructures and nanoparticles[54], which were found to be exceptionally active catalyst materials some 25 years ago, and emerging new materials like graphene and graphene oxide that could herald a next generation of 'green' carbon-based catalysts[55].

Photocatalysts, which use light and oxygen to remove pollutants from water, could also take a stride forward thanks to novel semiconductor/metal oxide nanoparticle composites[56]. In one recently started project, light-absorbing semiconductor/metal oxide nanoparticles are being incorporated into a liquid paint for coating photoreactors to provide a cost-effective water purification system.



Researchers from Ruhr-Universität Bochum in Germany are aiming as part of the EUR 3.7 million 4G-PHOTOCAT project to develop catalysts that detoxify water with the aid of sunlight and oxygen. The catalyst will be fabricated as a liquid that can be painted onto photoreactors. [Credit: Radim Beránek.]

51. *EU project* COORDSPACE.
52. *EU project* NEXT-GEN-CAT *(www.nextgencat.eu/)*.
53. *EU project* NANOSONWINGS.
54. *EU project* CO OXIDATION.
55. *EU project* GRAPH-CNTS-CAT.
56. *EU project* 4G-PHOTOCAT.

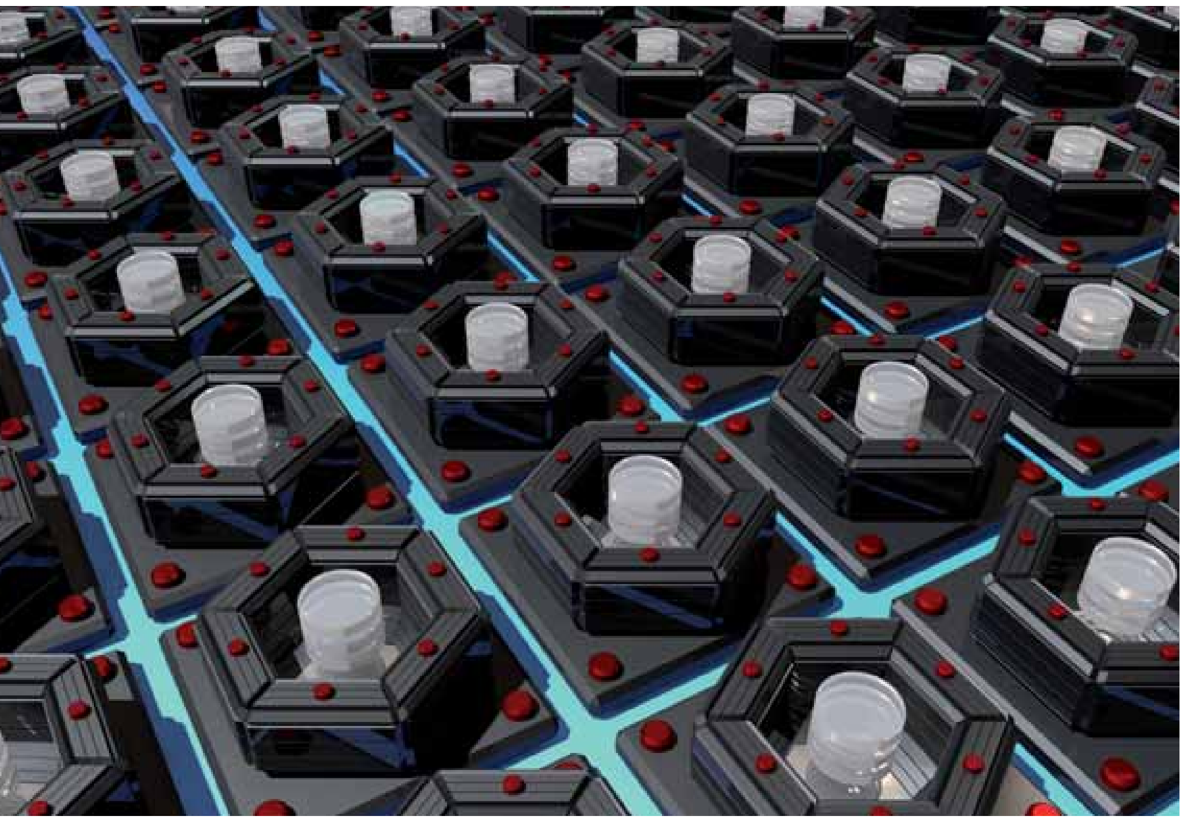
2.8. Manufacturing better: Industrial applications

Nanotechnology has the potential to improve other areas of industrial production, as well as catalysts, moving towards added-value innovative and sustainable processes that use less energy and raw materials. As well as harnessing nanotechnology in existing industrial processes, there is also a growing need to produce nanomaterials themselves on an industrial scale. Integral to this is the safe handling nanomaterials and the safety of products throughout their entire lifecycle.

One of the EU programme's key objectives is the scale-up of nanotechnology-based processes to pilot-line production. The impact of nanotechnology is staggeringly broad in this context, ranging from the production of electrochromic eyewear[57] all the way through to the use of smart magnetic particles for separation and extraction in biotechnology, food and pharmaceutical applications[58]. Other pilot-line projects aim to incorporate nanoparticles into papermaking[59] and nanomaterial-based fluid lubricants[60].

Meanwhile, other research efforts are focusing on a broad sweep of products and processes from life-saving antimicrobial textiles[61] (see textbox) to metal-nanoparticle coatings conveying high temperature resistance on gas and steam turbines, aircraft engines, boilers, waste incinerators and fire protection materials[62].

57. *EU project* INNOSHADE *(www.innoshade.eu/).*
58. *EU project* MAGPRO^{2}LIFE.
59. *EU project* SUNPAP *(http://sunpap.vtt.fi/).*
60. *EU project* ADDNANO *(https://sites.google.com/site/addnanoeu/).*
61. *EU project* NANOBOND *(www.nanobond.org/).*
62. *EU project* PARTICOAT *(www.particoat.eu/).*



Nanomaterials could also provide a solution to the problem of metal corrosion, which affects many sectors and costs some 3-4% of GDP worldwide a year. Nanostructured coatings could offer corrosion resistance to high-precision mechanical parts, aircraft brake systems and gas-handling components[63], while coatings for steel parts based on nanoceria, nanoclay and conductive polymers could avoid currently used toxic and hazardous compounds[64].

Texturing surfaces on the nanoscale either physically or chemically can bring other unique properties. By creating a regularly roughened surface, the so-called lotus effect ensures that dirt and water just run off. Italian automaker Fiat is already exploring these water-hating (or superhydrophobic) surfaces for car wing mirrors, while glass-makers are actively pursuing self-cleaning windows. Nanotextured surfaces even hold promise for prolonging the life and efficacy of medical devices[65].

Clean textiles keep hospitals safe: NANOBOND

There are twice as many deaths in Europe from hospital-acquired infections as from road traffic accidents. But this EUR 1.7 million FP7 NMP project has come up with a clever solution.

A novel nanoscale polymeric thin film coating for textiles holds on tightly to impregnated antimicrobial agents, improving efficacy while reducing leaching into the environment during washing.

The treatment could be applied to all types of hospital textiles from sheets to compression socks. The soft nanotechnology based polymer coating is now being commercialised.

www.nanobond.org/

The lotus effect, shown here, is being put into action on car wing mirror casings in the NANOCLEAN project.

Meanwhile, composite materials – incorporating novel carbon materials like nanotubes or fibres – promise lighter aircraft, improved fuel economy and reduced emissions[66]. Nanocomposites and coatings based on polyester resins and nanoclays provide another set of useful properties – fire retardency. Adding nanoparticles to thermoplastic polymers improves resistance to fire without resorting to halogen-based retardents, which have raised health and environmental concerns over the production of toxic compounds if they do ignite (see textbox).

Carbon-based nanocomposites could also find application in diverse areas from antistatic packaging for electronic goods to scaffolds for tissue engineering. Adding carbon nanotubes to thermoplastics holds promise for new composites for the automotive, rail, space, civil engineering and biomedical sectors as well[67]. Different filler and matrix choices can yield radically different materials. For example, wrapping sugar molecules – or polysaccharides – embedded

Putting out the fire: POLYFIRE

Fibre-reinforced polyester composites are widely used but are highy flammable and release toxic halogen-based species during combustion.

A new nanoparticle-reinforced polyester composite with improved fire retardency without toxic additives is being developed as part of a EUR 2.3 million FP7 NMP project, which could save thousands of lives and billions of euros a year. The halogen-free composite is now being tested in the highly demanding construction, rail and marine sectors.

www.polyfireproject.eu

63. *EU project* CORRAL.
64. *EU project* STEELCOAT *(http://steelcoatproject.com/).*
65. *EU project* NANOCLEAN *(www.nanoclean-project.eu/).*
66. *EU projects* LAYSA *and* ELECTRICAL *(www.electrical-project.eu/).*
67. *EU projects* HARCANA *(www.harcana.eu/) and* M-RECT *(www.mrect.risk-technologies.com/).*

A new wave in shipping: AMBIO

Biofouling – the build up of marine organisms on ships' hulls – can increase fuel use by up to 40% to maintain normal speeds, wasting European ship-owners tens of billions a year in unnecessary fuel costs. But a novel coating technology developed by this EUR 11.9 million FP6 project could provide a nontoxic and more efficient solution.

Marine organisms simply slip off the nanoparticle coating without having to use a biocide. The new approach, which is now being tested by industrial partner International Paint, could save 400 million tonnes of greenhouse gas emissions a year.

with nanoparticles around cellulose material yields a rather different bio-based smart composite that could find use in medical or electronic devices where its flame resistance, conductivity, antimicrobial activity and barrier properties are vital[68]. Basing composites on natural fibres and biopolymers could bring sustainability to numerous sectors, including automotives where such materials are alternatives to traditional plastic materials used for door panels, dashboards and other internal fittings[69], as well as household appliances[70].

Even the most traditional of materials like stone and cement are getting a nanoscale makeover. Nanocoatings are being developed to help in the conservation of stone buildings[71] and fibre-reinforced concrete is being advanced from its position as a 'dirty' material emitting nearly a tonne of carbon dioxide for every tonne produced to a cleaner, more sustainable one. Another project aims to create a nanoscale 'foam' core coated with a nanoclay fibre-reinforced cement 'skin', which can be produced in a low-energy extrusion process, minimising the use of environmentally unfriendly additives[72].

Nanomaterials are also proving their worth as exceedingly fine sieves to clean up water and separate gases. The nanosized pores in polymer- or silicon-based membranes can be used to trap unwanted elements from water[73] or separate gases like hydrogen and carbon dioxide in industrial processes[74]. One of the potentially most useful applications of these ultrafine membranes is in a process known as electrodialysis, where industrial waste material (usually salts) is removed from wastewater streams[75].

To serve new industrial applications with the large-scale quantities of nanomaterials needed, new manufacturing processes are required. Much effort is being directed at developing reliable means of producing various nanomaterials on a large scale, from inorganic nanotubes and ceramics to carbon-based nanomaterials and nanostructured metal alloys. Research activities are looking at cutting-edge materials like graphene, for example, which holds promise for a number of fields[76]. EU-backed projects are exploring roll-based chemical vapour deposition of graphene[77] and mass production of carbon nanotubes using wafer-scale equipment developed for the semiconductor chip industry[78].

Wood gets a new lease of life: SUSTAINCOMP

What unites a bus seat and a violin fingerboard? Both can now be made out of a new nanocomposite using wood fibres to reinforce a bioplastic thanks to a EUR 6.5 million FP7 NMP project. The reduced weight cuts fuel use in automotive applications and avoids the use of rare woods, while still providing outstanding acoustic properties.

"SUSTAINCOMP [will] open new possible business areas for the European forest-based industry," says coordinator Mikael Ankerfors of project partner Innventia.

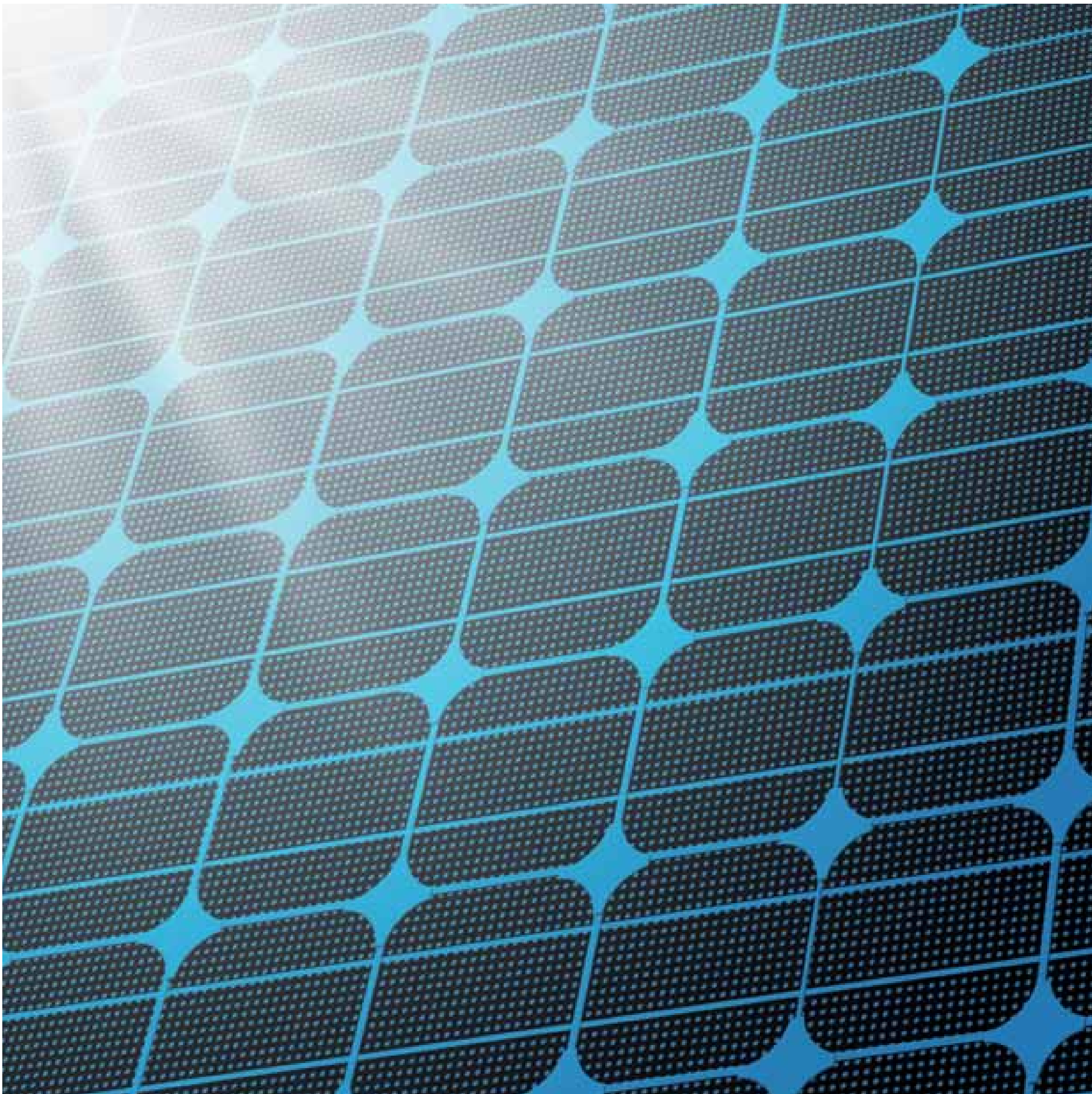
www.sustaincomp.eu/

68. *EU project* CP-IP.
69. *EU project* ECOPLAST *(www.ecoplastproject.com/).*
70. *EU project* BUGWORKERS *(www.bugworkersproject.eu/).*
71. *EU project* STONECORE *(www.stonecore-europe.eu/).*
72. *EU project* FIBCEM *(www.fibcem.com/).*
73. *EU project* WATERMIM *(http://lpre.cperi.certh.gr/watermim/).*
74. *EU project* SELFMEM *(www.selfmem.eu/).*
75. *EU project* NEW ED *(www.new-ed.eu/).*
76. *EU project* GRAPHENOCHEM.
77. *EU project* GRAFOL *(www.grafol.eu/).*
78. *EU project* TECHNOTUBES.

2.9. Less is more: Energy and environment

In coming decades, providing a sustainable energy supply to Europe is going to become a major economic and societal challenge. Climate change will necessitate breakthroughs in sustainable energy conversion, energy storage and carbon capture. The green, clean tech sector is also one where Europe could score major economic benefits and secure a significant proportion of the multibillion-dollar global market. Meanwhile, the growing global population and its demand for clean water is turning desalination and wastewater treatment into an area of pressing interest. Here nanotechnologies could aid in the production of drinking water in more efficient and economical ways and in the decontamination of polluted water streams.

Photovoltaic solar cells promise to be a major contributor to future energy supply, but the current 10-20 GW of installed power needs to be radically ramped up. A significant expansion of solar power will require a radical reduction in material and manufacturing costs. In the path towards highly efficiency photovoltaic cells providing power at less than $1/watt, there are a number of key challenges. One of those is to find alternatives to crystalline silicon for solar cells without compromising efficiency.



Printing solar cells: NOVA-CI(G)S

Inkjet printing could reduce the costs of producing new types of thin-film photovoltaic cells and make roll-to-roll fabrication of thin-film devices a reality.

This EUR 5.5 million FP7 NMP project could take solar module costs of CIGS to below 0.8 €/Wp.

www.tu-chemnitz.de/mb/DigiTech/ projects/ project-nova-cigs.php

Initially, improvement is likely to come from switching from current bulk silicon to thin-film devices. Silicon thin film devices currently show limited conversion efficiencies, but radical new synthesis routes could improve this problem[79]. Alternatively, other thin-film materials, like cadmium telluride (CdTe) and copper indium gallium selenide (CIGS) are moving into commercial production. CIGS has many advantages, but commercialisation continues to lag behind because costly and complex vacuum-based deposition processes are required (see textbox). New vacuum-free and environmentally friendly production routes to CIGS solar cells are, therefore, a high priority[80]. Meanwhile, the already-promising properties of CdTe could be boosted through nanostructuring[81].

Solar cells based on plastic and solution-processable inorganic materials provide another route to cost-effective production, but require a paradigm shift improvement in device performance[82]. Hybrid polymer-inorganic devices that use organic dyes to facilitate energy conversion – known as dye-sensitized solar cells – offer perhaps the greatest hope of improvements in efficiency. But adding semiconducting quantum dots to polymer-based solar cells could also boost performance[83]. While much of the impetus here is to move away from traditional silicon-based solar cells, silicon could still provide a route to cost-effective photovoltaics if nanocrystals could be harnessed in hybrid devices[84]. By reducing the amount of silicon used, costs can be cut while still exploiting the material's high conversion efficiency and low environmental impact.

Simultaneously, research efforts are also investigating other routes to high-efficiency, low-cost solar cells using semiconducting nanowires[85], the plasmon effect[86] and semiconductor quantum dots for light harvesting[87].

As well as improving renewable energy technologies, new materials are urgently needed that boost energy efficiency and capture energy that would otherwise go to waste. Thermoelectric devices require no fuel and have no moving parts, but can recapture or 'harvest' energy that would otherwise be lost, for example from the flue gases venting from power plants to vehicle exhaust[88]. Embedding nanoparticles in thermoelectric alloys could create nanocomposites able to perform efficient waste heat recovery from high-temperature industrial processes and automotive engines[89]. Regular arrays of silicon-germanium nanowires and quantum dots, or superlattices, could even harvest excess heat from microelectronic chips to provide a small-scale on-chip energy sources[90]. As well as on-chip sustainable energy generation, the set-up could lead to thermoelectric generators for domestic or industrial use.

Concerns over local air quality and global warming have focused attention on emissions from road transport. An alternative to gasoline is urgently needed to tackle these issues. In the short-term, battery-powered hybrid and plug-in electric vehicles are already on the market but serious improvements in these technologies are required for mainstream adoption. Further down the road, hydrogen offers a like-for-like replacement fuel for gasoline, but major challenges remain in its storage, production and delivery.

79. EU project ROD-SOL *(www.rodsol.eu/).*
80. EU projects SCALENANO *(www.scalenano.eu/) and* NOVA-CI(G)S.
81. EU project PHOTORODS.
82. EU project HYPER *(www.hyperproject.eu/).*
83. EU project POLYDOT.
84. EU project PHOTOSI.
85. EU projects UPCON *and* SOBONA.
86. EU project SOLAMON.
87. EU project EXCITONIC SOLAR CELL.
88. EU project NEXTEC (www.eu-nextec.eu/).
89. EU project NEAT *(www.neat-project.eu/).*
90. EU project GREEN SILICON *(www.greensilicon.eu/).*

Solar power on the rise:
COST-EFFECTIVE

What if the facades of high-rise buildings could generate energy? This EUR 7.5 million FP7 NMP project coordinated by the Fraunhofer Institute for Solar Energy Systems ISE aims to accomplish exactly that by combining transparent solar thermal collectors, air-heating vacuum tube collectors, photovoltaics, natural ventilation systems with integrated heat recovery and heat pump technologies.

The integrated renewable energy solution for high-rises has been tested on real buildings in Spain and Slovenia, where solar cooling chillers driven by facade collectors have been demonstrated for the first time.

www.cost-effective-renewables.eu/

Credit: Slovenian National Building and Civil Engineering Institute ZAG.

With a new generation of battery-powered vehicles taking the road, a concerted effort is underway to improve the lithium-ion batteries on which they rely. The typical lithium-ion battery vehicle currently has a range of less than 100 miles and takes around 8 hours to recharge. But a number of efforts are underway to improve that performance radically[91], including the use of recyclable carbon-based hybrid nanocomposite materials and processing methods, which could cut the costs of batteries by up to 150 €/KWh[92]. Lithium-ion batteries are often supplmented in vehicles with supercapacitors to supply short bursts of power during acceleration and recover braking energy. Ultimately, if supercapacitors based on nanostructured carbon materials, including graphene, could be designed to hold more energy they could supplant batteries altogether[93].

Meanwhile, biofuels derived from biomass feedstocks – plant materials, agricultural and domestic waste, and even algae – are being added into conventional gasoline supplies to reduce oil usage and greenhouse gas emissions. Nanotechnology is supporting this effort through the development of improved nanocatalysts and nanoporous molecular sieves used in the production process[94].

Beyond battery-powered vehicles, hydrogen-powered fuel cells are a very attractive future option because hydrogen is completely emission free – producing only water vapour as a waste product – and can be used in an engine and delivered to consumers much like gasoline. There are many technological challenges that must be solved before fuel cell vehicles can be mass-produced – and nanotechnology can help in a number of ways. Nanoporous materials, like carbon nanostructures, metal organic frameworks, boron nitrides and other nanocomposite materials (see textbox) are all being explored as storage materials[95]. Meanwhile, semiconducting chalcogenide nanotubes and nanowires could also enable efficient production of hydrogen via artificial photosynthesis[96].

Complex approach to hydrogen storage:
NANOHY

Nanocomposite materials based on complex hydride particles held in place by nanocarbon templates or polymer layers could be a viable option for hydrogen storage.

This EUR 2.4 million FP7 ENERGY project culminated in the construction of a test tank that supplied a fuel cell for 48 hours.

91. *EU project* LABOHR *(http://labohr.eu/).*
92. *EU project* SOMABAT *(http://somabat1.ite.es/).*
93. *EU projects* AUTOSUPERCAP *(http://autosupercap.eps.surrey.ac.uk/),* 2DNANOCAPS *and* ELECTROGRAPH *(www.electrograph.eu/).*
94. *EU projects* SUPRA-BIO *(www.suprabio.eu/) and* C3ENV.
95. *EU project* HYPOMAP *(www.jacobs-university.de/ses/theine/projects/HYPOMAP).*
96. *EU project* SOLAR BIO-HYDROGEN.

As energy becomes an increasingly precious commodity, using it efficiency is a growing preoccupation. The EU has cemented this endeavour into the legislature with a 20% energy reduction target for 2020. Homes and buildings are one of the single largest consumers and wasters of energy. Nanotechnology is helping in the drive towards more energy efficient buildings through novel insulating nanomaterials. Nanofoams, aerogels and aerogel composites could make durable vacuum insulation panels up to four times more efficient than current technologies[97]. In hotter climates, meanwhile, metal-oxide based coatings for external walls, facades, roofs and even internal walls and tiles that reflect sunlight and heat could lead to significant energy savings[98].

Along with energy, the provision of clean water supplies is going to become a growing concern in the future. Currently, 1.2 billion people lack access to safe drinking water and clean supplies is some parts of the world are already being put under pressure. Nanomembranes, already mentioned as a promising route for cleaning up industrial wastewater streams, can also be applied to the supply of clean drinking water. Research efforts are pursuing low-fouling nanoscale-honeycomb ceramic membranes[99] and novel biodegradable 'green' bio-based filters and adsorbent materials[100], among others, to remove toxic chemicals, heavy metals, pesticides and fertilizers from drinking water. In a similar approach, a clever water treatment system that uses sunlight to trigger a nanomembrane impregnated with a photocatalytic material to simultaneously filter out and kill micro-organisms, decompose organic pollutants and oxidize dissolved metals is being tested in the Middle East and Africa[101].

97. *EU projects* NANOINSULATE, AEROCOINS, HIPIN *and* NANOFOAM.
98. *EU project* COOL-COVERINGS *(www.coolcoverings.org/).*
99. *EU project* CERAWATER *(www.cerawater.eu/).*
100. *EU project* NANOSELECT *(http://nanoselect.eu/).*
101. *EU project* NATIOMEM *(www.natiomem.eu/).*

2.10. Investigating the nanoscale: Tools

A revolutionary microscope developed in the 1980s, the scanning probe microscope, has been giving scientists a novel view of materials on the nano- and atomic scale ever since. Rather like a record player, the scanning probe microscope drags a nanoscopic tip over the surface of a sample material, gathering a wealth of different information as it goes. By collecting different types of information from the tip, tapping the tip on the surface instead of dragging it or using the tip to inject current into a sample, an array of diverse techniques is possible that have been central to the development of nanotechnology.

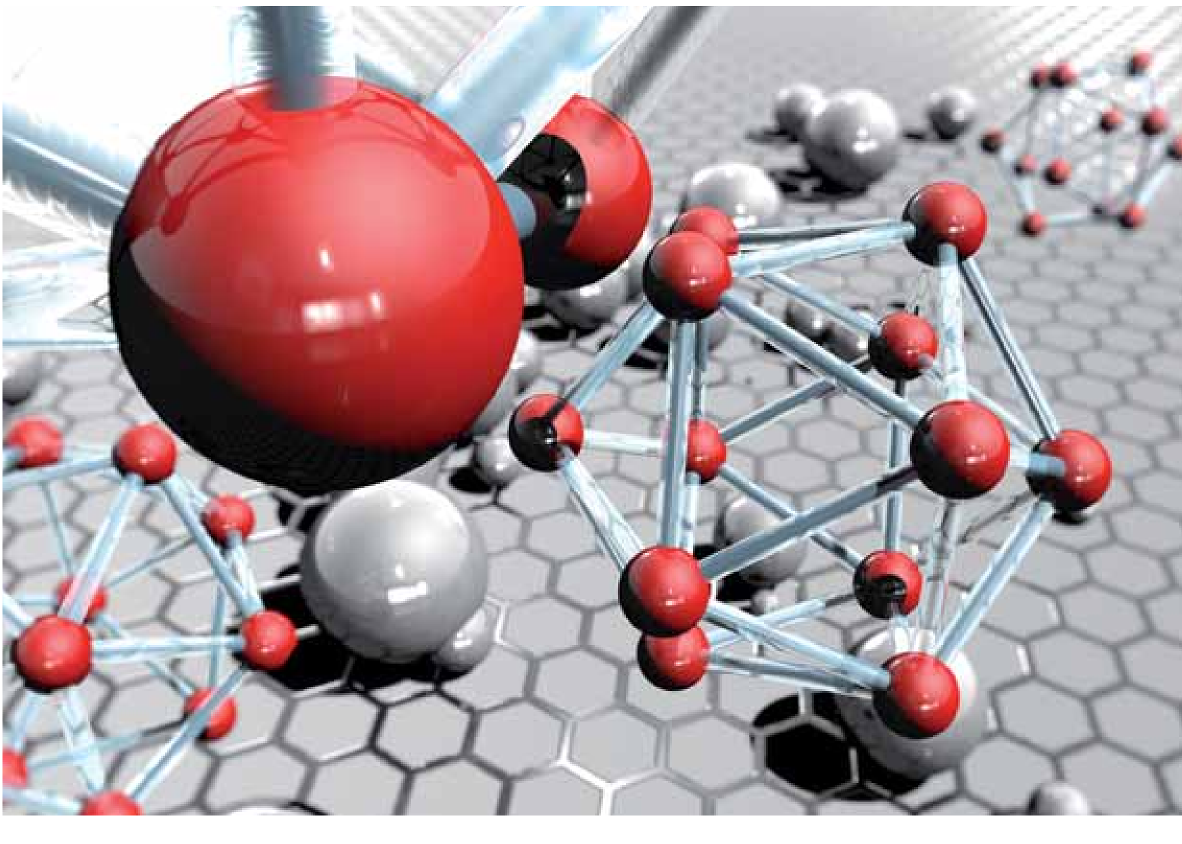
As control of molecules and atoms at the nanoscale becomes more and more exquisite, imaging techniques are having to develop to keep pace. For example, dragging a sharp tip over biological materials can be damaging so atomic force microscope probes have been developed that gently tap the surface instead. Speeding up the tapping of the tip to very high frequencies into the gigahertz range could enable unprecedented imaging of biological and chemical systems at the nanoscale[102].

Shedding new light on 3D imaging: TERATOMO

Bombarding materials with infrared and terahertz light provides a map of chemical make-up, crystal structure and conductivity. This EUR 1.5 million FP7 ERC IDEAS project is using a sharp tip to focus light to a nanoscale beam, which can provide unprecedented resolution.

"This will allow imaging inside nanostructures in a similar way as computed tomography (CT) sees inside the human body," explains researcher Rainer Hillenbrand of CIC nanoGUNE in Spain.

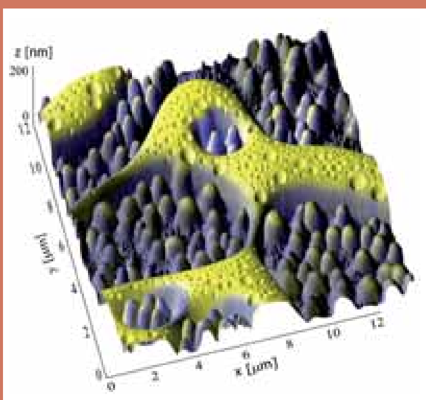
102. EU project SMART.



Mapping surface chemistry: 3D NANOCHEMISCOPE

Surface chemical analysis techniques like time-of-flight secondary ion mass spectrometry (ToF-SIMS) can become distorted in three dimensions. By combining with scanning force microscopy (SFM), the EUR 4 million 3D NANOCHEMISCOPE FP7 NMP project will create a technique able to provide a distortion-free, three-dimensional chemical map of a sample surface.

A working prototype of the combined instrument has been built and is being used to perform showcase experiments. "The combination of local physical properties from SFM operating modes with chemical properties opens up wide possibilities," says researcher Laetitia Bernard of Empa. The new approach will help understand nanoscale mechanisms in organic and inorganic optoelectronic devices, solar cells, memory devices and even materials like cement.



A polymer blend used in organic solar cells, with colours revealing two chemical species on the surface. Scale: 12 x 12 µm², 200 nm high.

www.3dnanochemiscope.eu/

But it is not just the surface of materials that researchers want access to, it is also vital to be able to 'see' inside objects in three dimensions. One such effort is using microwaves to probe the three-dimensional structural and chemical constitution of materials at the nanoscale[103]. Optical spectroscopy techniques, where the interaction of light or electromagnetic radiation with a sample provides information about it, are also being pushed to provide three-dimensional mapping on the nanoscale (see textbox).

Ideally, though, the researcher would like a single instrument that could provide many different kinds of analysis simultaneously. By bringing together a technique that can provide information on nanoscale surface chemistry and surface morphology with a second that strips off a layer of material at a time, a three-dimensional picture of the chemical species in a sample can be built up (see textbox). Meanwhile, another effort hopes to turn the microscope into a fully functional nano-laboratory integrating a focused ion beam, scanning electron microscope and nano-manipulator with scanning probe microscopy capabilities[104]. These tools allow the examination of samples in completely new ways: the electrical and mechanical characteristics of nanowires can be measured, as well as their distribution, while the top layer of molecules can also be removed to build up a three-dimensional picture of the material. New instruments of this type could become standard analytical tools within a few years.

103. *EU project* V-SMMART NANO *(www.vsmmartnano.com/).*
104. *EU project* FIBLYS *(www.fiblys.eu/).*

2.11. Making it safe: Health, safety and environment

Despite the exciting potential of nanotechnology, the scientific community, regulatory authorities and general public are more aware than ever before about the potential risks inherent in any new, emerging technology. Surface and quantum size effects take over when materials move into the nanoscale regime, making predictions of their behaviour in the body and other biological systems particularly complex. Early results have been conflicting, but progress is being made in understanding interactions of nanomaterials with biological systems. The EU has been quick to ensure that health, environmental and consumer protection is core to its nanotechnology programme.

Research efforts are both assessing the ecotoxicological effects of engineered nanomaterials[105] and seeking to develop evaluation tools and techniques. Other efforts aim to determine the effects of nanoparticles on key human tissues such as the gastero-intestinal (GI) tract, liver and endothelium[106], as well as on the pulmonary, hepatic, renal, cardiovascular and developmental systems[107].

Possible exposure to engineered nanoparticles in the workplace is a particular worry as manufacturing ramps up. But there is a shortage of reliable, cost-effective ways of assessing nanoparticle levels in workplace air in real time (see textbox).

A safe place to work: NANODEVICE

Monitoring devices able to detect airborne nanomaterials in workplaces can cost EUR 70 000-300 000. But this EUR 9.5 million FP7 NMP project hopes to reduce these costs to a more affordable EUR 150-15 000.

Researchers have come up with 14 different devices for measuring concentrations of airborne engineered nanomaterials and a standard sample collection strategy, which project coordinator Kai Savolainen of the Finnish Institute of Occupational Health says will have a huge impact on the safety of workers in the emerging nanotechnology industry. The ability to assess exposure in SMEs as well as large organisations will ultimately allow the introduction of regulations setting safe occupational levels for workplaces, workers or consumers.

www.nano-device.eu

Weathering the risks: NANOPOLYTOX

Polymer nanocomposites contain carbon nanotubes, nanoclays or metal oxide nanoparticles. But what happens to these nanomaterials when the composite weathers and breaks down?

This is exactly what a EUR 2.4 million FP7 NMP project has set out to discover. The project will monitor the toxicity of nanomaterials during their entire life cycle from synthesis to recycling and disposal. The outcomes will inform predictive models of the fate of nanomaterials in the environment.

www.nanopolytox.eu/

A parallel concern is what happens to nanomaterials during their lifecycle, especially when they are recycled or disposed of, as some applications – namely fuel additives, personal care and antibacterial products – preclude reuse. The interest here is not only potential effects on humans but also on the wider environment – on water, soil and air[108]. As well as a comprehensive understanding of the impact of different types of nanoparticle on the environment, these projects promise to generate standard risk assessment procedures and protocols (see textbox, below).

105. *EU projects* ENVNANO *and* NANORETOX *(www.nanoretox.eu/).*
106. *EU project* INLIVETOX *(www.inlivetox.eu/).*
107. *EU project* ENPRA *(www.enpra.eu/).*
108. *EU projects* NEPHH *(www.nephh-fp7.eu/) and* ENNSATOX *(www.ennsatox.eu/).*

The EU's FP7 funding initiative in Health, Safety and Environment (HSE), has pursued a cluster approach to its activities, grouping together related projects to mutually inform and support one another. The outcomes from the research-based efforts will be fed into the EU's Code of Conduct for responsible nanoscience and nanotechnology research, which draws in relevant information from as wide a base as possible. The efforts on information gathering also encompass a nano-related health-environment database[109], web-based knowledge system covering public health information[110], searchable databases of reports and articles on health and safety aspects of nanomaterials[111], and a directory of research projects on the risk assessment of nanomaterials[112]. The comprehensive effort is contributing to the international regulatory framework, supporting ISO standards relating to nanotechnology. The key issue in this strand of EU-funded research is to reduce the uncertainty around the safety and health impacts of engineered nanomaterials and enable these factors to be taken into consideration when a new material is being designed.

109. EU project NHECD *(www.nhecd-fp7.eu/).*

110. EU project EUPHIX.

111. EU project SAFENANO *(http://safenano.org/).*

112. EU project OECD-WPMN.

2.12. Talking it over: Communication and societal impact

The explosion in nanotechnology and the race to get nano-enabled products to market has raised concerns that unless potential risks are discussed in a transparent manner there could be serious damage to consumer confidence. The scientific research funded by the EU is underpinned by complimentary activities exploring the ethical, legal and social aspects of nanotechnology, as well as efforts to communicate its benefits to a wider audience.

Previous efforts have sought to bring together environmental NGOs, trade unions, academic researchers and other stakeholders to discuss the potential impacts of nanotechnology on health and the environment[113]. Some of the greatest potential benefits but also the most pressing concerns arise in the nanomedical field, so the current FP7 has established the ***Nanomed Round Table*** to bring together patient groups, regulatory bodies, health insurers and policy makers, as well as experts on ethical, regulatory, social, and economic issues. Through information gathering and discussions, the project aims to set clear recommendations for decision-making on nanomedical issues across Europe.

Parallel efforts aim to bring uniformity of approach to the nano-research and development enterprise, such as coordinating the metrology of nano-manufactured products[114] to support future regulations or creating hubs that connect disparate EU research programmes, industries, SMEs, NGOs, financial institutions, research institutions and universities. The ***QNANO*** project, for example, is setting out to establish a pan-European infrastructure for sharing scientific best practice in nanomaterials safety testing.

Communicating the potential benefits of nanotechnology to industry and the wider public[115] is the other main strand of the EU's support initiative. While Europe's research efforts in this arena continue to impress, exploitation of this scientific expertise by the industrial sector could be improved upon. One priority for current and future initiatives, therefore, is to lower the barriers to the transfer of nanotechnology into industrial settings and set out best practices[116].

113. *EU FP6 projects* NANOCAP *(www.co-nanomet.eu/) and* NANOIMPACTNET *(www.nanoimpactnet.eu/).*
114. *EU project* CO-NANOMET.
115. *EU projects* NANOYOU *(http://nanoyou.eu/) and* NANODIALOGUE *(http://nanodialog.eu/).*
116. *EU projects* NANO2MARKET *(www.nano2market.eu/),* MANANO, PRONANO *(www.pronano.eu/) and* NANOCOM *(www.nanocom-eu.org/NanoCom/Homepage.html).*

2.13. Delivering a nano-enabled future now

The EU's research funding initiative, FP7, with its EUR 50.5 billion budget, has supported some 19 000 projects involving over 79 000 organisations – universities, research institutions and businesses – since 2007. Moreover, the careers of at least 55 000 researchers have been supported through the programme, in particular its ERC IDEAS and Marie Curie Fellowship grants.

Europe has key strengths in medicine, biotechnology, ICT and advanced industrial manufacturing. The previous FP6 and current FP7 programmes have tapped into these strengths, while building expertise and knowledge in new areas. Technologies arising out of research undertaken as part of FP6 are already being commercialised and others are likely to follow from the current programme.

Within a decade, new therapies to treat the 44 million Europeans with hearing loss could emerge from one project that has developed biodegradable nanoparticles for targeting the inner ear and innovative cochlear implants able to deliver drugs[117]. Meanwhile, a portable, fast MRSA testing kit is now on the market that came out of an effort to combine biosensor technology with nano-engineered structures integrated onto a microfluidic lab-on-a-chip platform[118].

At the opposite end of the technological spectrum, nanotechnology has also informed the development of new membranes capable of capturing carbon dioxide from the flue gases of fossil-fuel power stations. A truly European effort drawing in partners from across the region has successfully demonstrated nanoscale-polymer membranes able to withstand long-term exposure to industrial flue gases and capture carbon dioxide more efficiently and cheaply[119].

117. *EU project* NANOEAR *(www.nanoear.org/).*
118. *EU project* DINAMICS *(www.dinamics-project.eu/).*
119. *EU project* nanoGLOWA *(www.nanoglowa.com/)*

3. FUTURE DIRECTIONS – WHERE NEXT?

3.1. Future economic benefits for Europe

In order to make it big, Europe must go smaller; carving out a share of the emerging nanotechnology market, which heralds a new industrial and technological revolution. According to current estimates, the global market for nano-based goods is already over EUR 1 trillion, with a compound annual growth rate (CAGR) of 50% since 2009. Specific markets, like nanomaterials and printed electronics, could be worth around USD 45-47 billion by 2018[120]. But these predictions only take into account primary markets, which are likely to represent a mere fraction of the entire nano-related sector.

While Europe has an unparalleled research base in nanotechnology, thanks to programmes like FP 6/7, it must capitalise on this expertise to maintain its global position. The semiconductor sector, for example, supports over 100 000 direct jobs in the region and thousands more indirectly. If the EU as a region does not engage fully with the nano-revolution in chip technology as it moves out of the current CMOS regime into new nanomaterials, nanofabrication techniques and ultimately a quantum paradigm of operation, the US and Asia could take a significant technological lead. Europe must secure its role in other emerging nano-markets as well, taking the opportunity to develop profitable companies in new materials, processing equipment and device technology.

Europe's pharmaceutical industry, for example, stands to benefit from the growth in the nanomedicine sector, which is predicted to show sales of USD 130.9 billion by 2016[121], particularly in cardiovascular treatments, anti-inflammatories, anti-infectives, anti-cancer agents and central nervous system therapeutics. But while the region is at the forefront of research, it risks being usurped by the US, which is taking a lead in the number of patent filings and making rapid progress in commercialisation.

Nanotechnology also presents an opportunity to rejuvenate traditional industries, like chemicals and catalysts, papermaking, and agriculture, bringing innovations in sustainability, processing, energy efficiency, recycling, emissions control and waste treatment. These sectors stand to be transformed, giving Europe a clear margin of difference and added value over the global competition.

Solutions to the most major challenges facing Europe, a secure affordable energy supply and reduced greenhouse gas emissions, could also be presented by nanotechnologies and innovations in existing technologies. According to the International Energy Agency, some USD 36 trillion of investment is needed to overhaul the world's current energy system by 2050 and limit climate change to 2˚C[122]. While this represents an enormous challenge, it also presents an enormous technological opportunity: more efficient solar photovoltaics, wind turbines, energy conversion technologies, energy efficient insulating materials and carbon capture membranes, to name but a few, will all be required. In the next five to ten years alone, the low-carbon energy market, including energy efficient technologies and alternative fuel vehicles, could be worth USD 1-2 trillion[123]. As well as the economic opportunity and the environmental imperative, the EU also has a legal obligation, having pledged to a 20% reduction in emissions, increase in renewables and improvement in energy efficiency by 2020.

120. *IDTechEx, www.idtechex.com/*
121. *Nanotechnology in Medical Applications: The Global Market, BCC Research, www.bccresearch.com/*
122. Energy Technology Perspectives 2012, *International Energy Agency, www.iea.org*
123. Sizing the climate economy, *(2010), HSBC*

3.2. On the horizon – where next for nanotechnology?

Nanotechnology has exploded in recent decades and is now one of the centrepieces of the EU's research funding programme. With its broad reach across diverse fields, nanotechnology stands on the verge of launching a new technological revolution. But while Europe has embraced the exploration of the nanoscale, European Research, Innovation and Science Commissioner Máire Geoghegan-Quinn warns that the region faces an "innovation crisis".

The Commission is responding with a major new financial instrument, Horizon 2020, which will supersede the successful FP research funding initiatives when they come to a close at the end of the year. Running from 2014 to 2020, the proposed EUR 80 billion initiative aims to harness research and innovation to drive new growth and jobs in the region. For the first time, Horizon 2020 will bring together all research and innovation funding under one umbrella, including a EUR 24.6 billion dedicated science budget, EUR 17.9 billion for industrial innovation including a EUR 1.2 billion package specifically for small- and medium-sized enterprises (SMEs), and EUR 31.75 billion targeted at the most pressing issues facing Europe such as climate change, sustainable transport, renewable energy and the medical care requirements of an ageing population.

One of the already identified cornerstones of the Horizon 2020 programme, under the Future and Emerging Technologies (FET) competition, will be a EUR 1 billion, ten-year sustained initiative dedicated to the investigation and exploitation of the unique properties of graphene. This exceptional nanomaterial possesses such remarkable physical and chemical properties that it has been dubbed the wonder material of the 21st century with far-reaching potential in electronics, transport, energy and medicine. The 'Flagship' effort on graphene, which will involve over 100 research groups and 136 principle investigators including four Nobel Laureates, indicates just how important nanotechnology is and will be over the coming decades.

But while the clear priority of the new funding programme is to bridge the gap between research and the market, the central tenant of the European research effort remains excellent science, without which there can be no progress.

As Commissioner Geoghegan-Quinn, says:

"Knowledge is the currency of the global economy. If Europe wants to continue to compete in the 21st century, we must support the research and innovation that will generate growth and jobs, now and in the future."

European Commission

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KI-30-13-325-EN-C

This publication describes the unique nature of nanotechnology, bringing innovation to every aspect of human existence. The publication outlines nanoscience and nanotechnology dedicated research expenditure in Europe over recent years, in particular via the 7th Research Framework Programme (FP7). An overview is given of the main sectors where nanotechnology is enabling significant progress. It highlights a selection of exemplary projects financed through FP7 that are representative of major research themes, such as nanoelectronics, nanophotonics, nanobiotechnology, nanomedicine, self-assembly, catalysts, industrial applications, energy and environment, tools for investing the nanoscale, health/safety/environment and communication/ societal impact.

Looking forward, the final chapter focuses on future economic benefits for Europe, such as improving health care, rejuvenating traditional industries and bringing solutions to the most major challenges facing Europe, a secure affordable energy supply and reduced greenhouse gas emissions.

Research and Innovation Policy

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