The effect of nanotechnology on mitigation and adaptation strategies in response to climate change

A.G. Mamalis,[1,*] J.J. Ramsden,[2] G.C. Holt,[3] A.K. Vortselas[4] and A.A. Mamali[5]

[1] *Project Center for Nanotechnology and Advanced Engineering, NCSR "Demokritos", Athens, Greece*
[2] *Cranfield University, Bedfordshire MK43 0AL, UK*
[3] *Collegium Basilea, Institute of Advanced Study, Basel, Switzerland*
[4] *Laboratory of Manufacturing Technology, National Technical University, Athens, Greece*
[5] *Cass Business School, City University, London, UK*

If one accepts that climate change is caused by excess carbon dioxide emissions mainly related to excessive energy consumption, reducing it is clearly one very useful way of mitigating climate change. The present work explores how mitigation as well as adaptation strategies for climate change might be transformed by enlisting the help of nanotechnology, the most significant breakthrough technology of the new century. A warning against the premature affirmation of benefits is given.

1. INTRODUCTION

A plethora of data accumulated over the past years has provided strong evidence that the Earth's climate is, globally, warming. Much evidence has been collected in the Fourth Assessment Report[1] of the Intergovernmental Panel on Climate Change (IPCC): during the past century, air and sea temperatures and sea levels have risen, while sea ice, glaciers and snow cover have shrunk, all to an unprecedented extent in historical times. Furthermore, the world is now experiencing more extreme weather patterns, with more intense and longer droughts, more extreme precipitation, and more very hot days and heat waves than hitherto.

The consequences of these changes are more frequent and dangerous floods and storms, stressed water supplies, a decline in agricultural productivity (and, hence, food security) and the

* Corresponding author. E-mail: mamalis@ims.demokritos.gr
[1] IPCC, *AR4 Synthesis Report* (2007), http://www.ipcc.ch

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spread of diseases. These in turn could lead to widespread poverty, population displacement, migration and violent conflicts.

Much attention has been paid to the correlation of climate change (as measured, e.g., by global mean temperature) with increased CO_2 emissions, which are mainly related to excessive energy consumption.[2] If this correlation is taken to imply causality, an effective response to climate change must combine *mitigation* strategies (centred on reducing energy consumption[3]), to avoid facing phenomena that are impossible to manage, with *adaptation* strategies, perhaps focusing on aid to developing countries, to manage the unavoidable effects.

The consensus of scientists and policymakers worldwide seems to be that nanotechnology is a platform technology that will be involved in the entirety of human industrial activity henceforth. It has enormous potential to help humanity reach a technological level where ongoing development will also be sustainable. *A fortiori*, nanotechnology can also be expected to contribute to the mitigation and adaptation strategies to combat climate change.

2. CLIMATE CHANGE AND SUSTAINABILITY

Before discussing the specific areas where nanotechnology could have an effect on climate change, the characteristics of the climate change problem have to be presented, the concept of sustainability has to be introduced and the available strategies for mitigation and adaptation have to be detailed.

2.1. CO_2 emissions—the greenhouse effect

After many years of intensive climate studies, it can be considered to be nowadays well established that global warming is already happening and is going to be a real global problem in the 21st century. More controversial, but nevertheless plausible, is the assertion that global warming is *caused* by the emissions of thermal balance-modifying agents (the greenhouse gases (GHGs): CO_2, CH_4, N_2O, chlorofluorocarbons (CFCs) and others, as well as carbon soot and water vapour) originating from human activity (Figure 1).

It has also been shown that, although the climate impacts of emissions will be long-lived and totally halting emissions will not lead directly to the stabilization of global temperatures or global sea level any time soon (Figure 2), it is feasible, even with current technologies, to stabilize global temperature to 2 °C above the current mean if emission reduction measures are quickly adopted (Figure 3).

2.2. Sustainability

The term "sustainability" refers to the quality of "keeping going over time or continuously" and is most aptly applied to life, which needs sustenance to keep going, but is also applied to other systems, such as the ecosystem, commercial enterprises and economic activity in general and

[2] G.C. Holt, J.J. Ramsden, Introduction to global warming. In: *Complexity and Security* (eds. J.J. Ramsden and P.J. Kervalishvili), pp. 147–184. Amsterdam: IOS Press (2008).

[3] F. Maltini, Climate change and the complexity of the energy global security supply solutions: the global energy (r)evolution. In: *Complexity and Security* (eds. J.J. Ramsden and P.J. Kervalishvili), pp. 185–217. Amsterdam: IOS Press (2008).

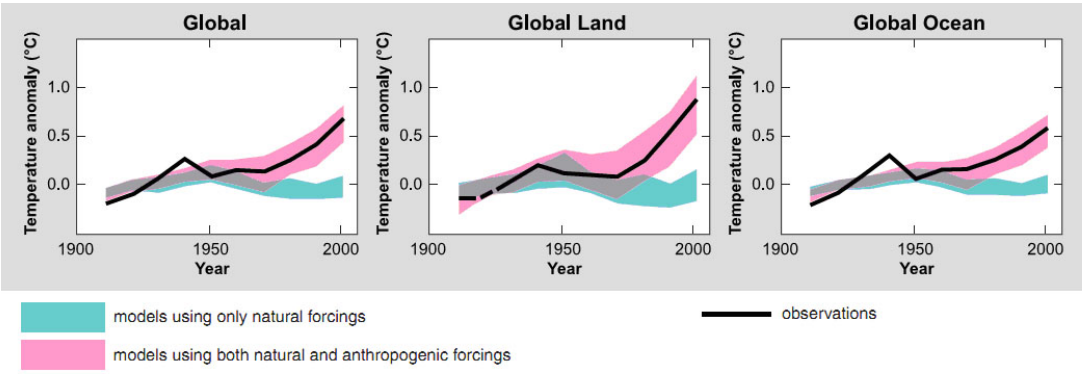

Figure 1. Aggregate results of climate models, compared to observed results.[4]

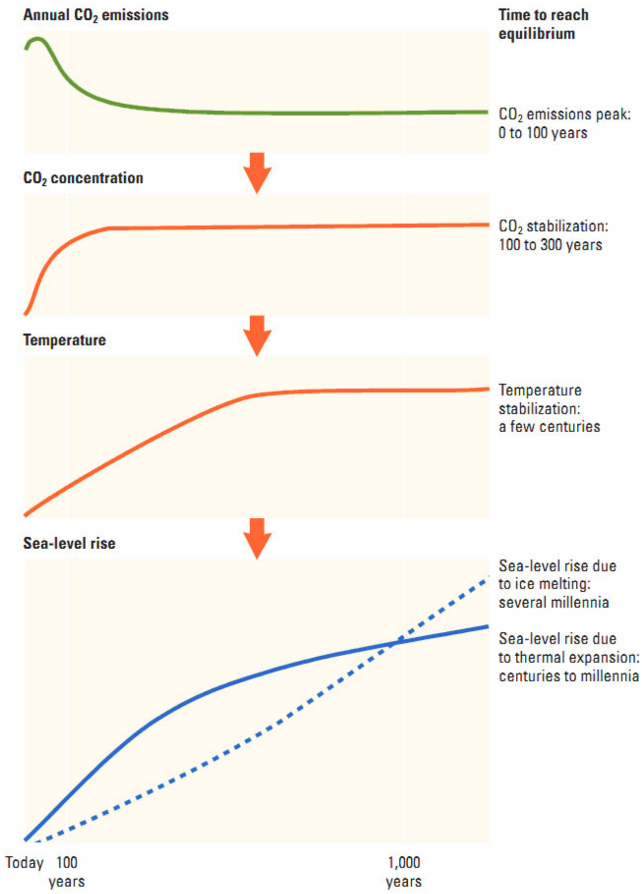

Figure 2. Climate impacts are long-lived: rising temperatures and sea level associated with higher concentrations of CO_2.[5]

[4] IPCC, *AR4 Synthesis Report* (2007). §2.4: Attribution of climate change (p. 40).
[5] World Bank, *World Development Report, Overview: Changing the Climate for Development* (2010).

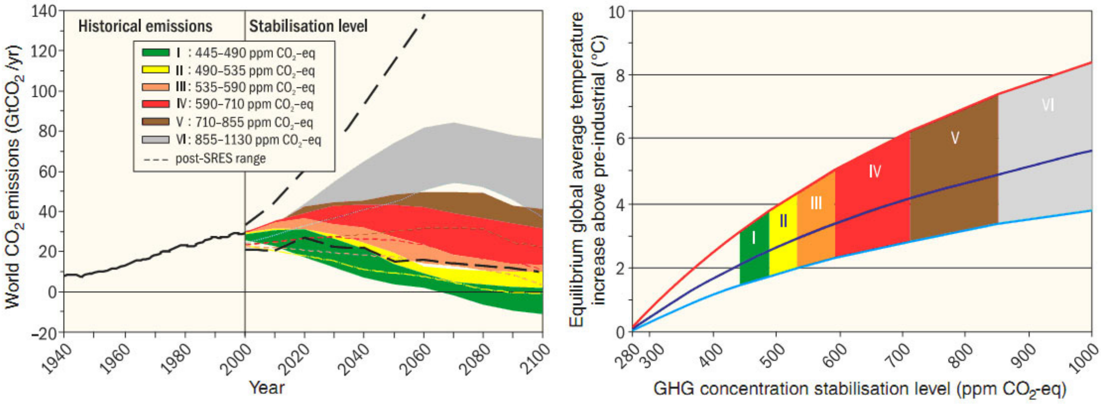

Figure 3. CO_2 emissions and equilibrium temperature increases for a range of emission stabilization levels.[6]

also to political systems, all of them being metaphors for life in some way.[7] More specifically, *environmental sustainability* aims at continuing industrial activity indefinitely without harm to the environment or at least maintaining the environment in a sufficiently healthy state to permit the continuing existence of our species, as opposed to that of each individual. *Industrial sustainability* refers to keeping a business going and ensuring the survival of its stakeholders (owners, directors, shareholders, employees and customers). It involves sustainably secure and risk-free access to resources, persistent demand at profitable output levels as well as the continuous creation of new markets. Sometimes these two categories of sustainability are in conflict, but sometimes they are aligned with one another.

There is a direct relationship between nanotechnology and sustainability. Sustainable industry ultimately needs to be based on "clean technology" (often called "cleantech" for short), meaning manufacturing technology that produces no waste and, hence, obviously less pollution, thus promoting environmental sustainability. Nanotechnology is deemed to be the ultimate cleantech since, in principle, only those atoms required for the finished product are actually used in nanoscale manufacturing processes (usually referred to as "nanofacture"). Also, nanotechnology products promise increased efficiency during use since they are smaller, hence requiring less energy to operate, which in turn implies fewer infrastructures. Thus, by deploying nanotechnology the goal of environmental sustainability can often be promoted without jeopardizing the goal of industrial sustainability.

2.3. Mitigation and adaptation strategies

A summary of the basic strategies that can be explored to address climate change will be presented here. *Climate change mitigation* is a strategy encompassing all efforts to postpone, neutralize and reverse the causes and effects of global warming (e.g., by reducing GHG emissions). *Climate change adaptation* is a strategy to prepare the global economic and civil infrastructure for the effects of global warming, in order to preserve lives, health and living standards.

6 IPCC, *AR4 Synthesis Report* (2007). §5.4: Emissions trajectories for stabilisation (p. 66).
7 J.J. Ramsden, What is sustainability? *Nanotechnology Perceptions* **6** (2010) 179–195.

2.3.1. Mitigation

If the world proceeds on the path of current climate change mitigation policies and the sustainable development practices already in effect, global GHG emissions will continue to grow over the next few decades. According to the Special Report on Emissions Scenarios (SRES) for unmitigated emissions[8] an increase of baseline global GHG emissions from 25% to 90% between 2000 and 2030 is projected. In a 2030 scenario for multigas mitigation, having estimated macroeconomic costs consistent with a stagnating global gross domestic product (GDP, between a 3% decrease and a small increase), the projected emissions trajectories point towards stabilization between 445 and 710 ppm CO_2-eq (carbon dioxide equivalents).[9]

2.3.1.1. Emissions reduction

Global GHG emissions have grown by 70% between 1970 and 2004. The largest contributor to this growth is the energy supply sector (an increase of 145%). The growth in direct emissions from transport in this period was 120%, from industry 65% and from land use, land use change and forestry 40%. Between 1970 and 1990 direct emissions from agriculture grew by 27% and from buildings by 26%, and the latter remained at approximately 1990 levels thereafter. However, the buildings sector has a high level of electricity consumption and hence its total impact on emissions is much higher.[9] A breakdown of the sources of global greenhouse gas (GHG) emissions can be seen in Figure 4.

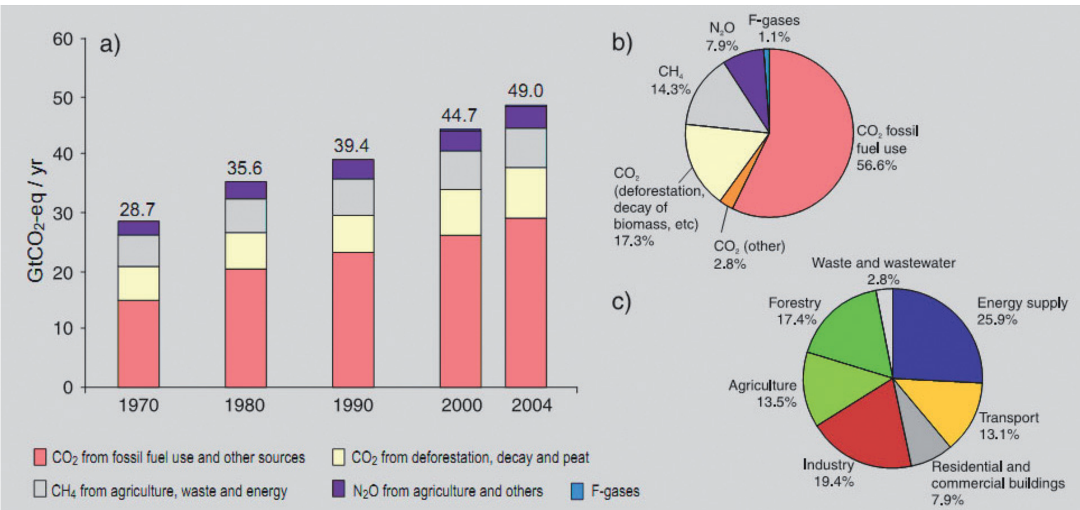

Figure 4. (a) Global annual emissions of anthropogenic GHGs from 1970 to 2004. (b) Share of different anthropogenic GHGs in total emissions in 2004 in terms of CO_2-eq. (c) Share of different sectors in total anthropogenic GHG emissions in 2004 in terms of CO_2-eq (carbon dioxide equivalents, obtained by multiplying the actual masses of the GHGs by their global warming potential (GWP)).[10]

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8 IPCC Data Distribution Center, *SRES (Emissions Scenarios)*, http://sedac.ciesin.columbia.edu/ddc/sres/
9 IPCC, *AR4 Synthesis Report* (2010). Work Group 3: Summary for Policymakers.
10 IPCC, *AR4 Synthesis Report* (2007). §2.1: Emissions of long-lived GHGs (p. 40).

Energy production and use are the biggest contributors to greenhouse gas emissions, and are expected to remain so in the future. Developed countries will continue to have higher energy use and emissions *per capita* (this is alternatively called a big energy and carbon footprint). Therefore, this is the most actively pursued area of possible emissions reduction. Technology solutions can be applied for: improved supply and distribution efficiency; fuel switching from coal to gas; nuclear power; renewable heat and power (hydropower, solar, wind, geothermal and bioenergy); and combined heat and power generation.

Efficient transportation technologies are typically some of the lowest-cost means of reducing carbon emissions but they are often not adopted, because of insufficient incentives for freight companies and passengers. The counterincentives, which may include price, speed and reliability, have to be identified and quantified, so that state interventions can be designed to negate them. In this respect, technological solutions not directly related to emissions reduction or efficiency but to other factors like reliability may be crucial for the success of mitigation strategies.

Land use changes in forestry and agriculture account for almost half of the emissions from developing countries. Better forestry and agricultural techniques offer cost-effective mitigation with the added benefits of improving livelihoods, reducing soil erosion and protecting biodiversity. These efforts often involve "low-tech" solutions, but can also widely benefit from breakthrough technologies—such as nanotechnology—which may bring about a paradigm shift in rural economies (this is sometimes called "leapfrogging" since it is not necessary to pass through the intermediate stages of traditional technological development).

2.3.1.2. CO_2 capture and sequestration

CO_2 capture and sequestration (CCS) labels a family of technologies that aim to alleviate the climate impact of burning fossil fuel by capturing the CO_2 at the point of emission and recycling it or placing it into stable storage. Most developed CCS strategies involve industrial-scale capture of concentrated emissions from what are usually referred to as "high profile point sources" such as fossil fuel power stations and cement, ammonia and iron production plants.[11,12] Presently, industrial plants rely on chemical absorption to separate carbon dioxide from other emissions. However, chemical absorption is expensive and energy-intensive, and has an independent, negative impact on the environment. The most immediate effect of nanotechnology in this area would be to replace current chemical-based carbon dioxide separation technology with membrane-based technology. Future plans envision direct filtration of the atmosphere, enhanced biomass production in forests and the sea and artificial photosynthesis.

2.3.1.3. Climate engineering

Climate engineering is a term covering all explicit human interventions that aim at controllably affecting climate parameters. It is considered to be the ultimate recourse of humanity if all other mitigation efforts fail. A wide range of geo-engineering options has been researched, such as ocean fertilization to remove CO_2 directly from the atmosphere, changing the Earth's albedo by

[11] N. Florin, P. Fennell, *Review of Advanced Carbon Capture Technologies*. Work Stream 2, Report 5A of the AVOID programme (2010). www.avoid.uk.net

[12] IPCC, *Special Report on Carbon Dioxide Capture and Storage* (2005).

dispersing particulate material into the upper atmosphere, and even extraterrestrial solutions, like deploying a cluster of satellites to provide shade. These options remain largely speculative and unproven, with the risk of unknown side-effects. Reliable cost estimates have not been published. The prospects of successful geo-engineering are, however, likely to be transformed by recourse to relevant nanotechnologies, which will enable their implementation at a meaningful scale and at reasonable cost.

2.3.2. Adaptation

Adaptation to climate change is going to be a game played on unequal terms. Developing countries are expected to be the ones hardest hit by climate change. Higher temperatures, changes in precipitation patterns, rising sea levels and more frequent weather-related disasters are expected to pose hazards for agriculture, food and water supplies. Developing countries, however, at present lack the scientific and high-technology resources required for adaptation. Nevertheless, there is now a view that adaptation efforts should be focused on protecting humanity's gains in the fight against poverty, hunger and disease, and the lives and livelihoods of milliards of people in developing countries.[13]

2.3.2.1. Securing food and water supply

Like in other sectors, nanotechnology promises to revolutionize the whole food chain—from production to processing, storage, and development of innovative materials, products and applications.[14] Although the emergent applications of nanotechnology are wide ranging, relatively few presently exist in the food and agricultural sectors. In an overview of more than 800 nanotechnology-based consumer products currently available worldwide, just around 10% are foods, beverages and food packaging products.[15]

However, nanotechnology-derived products and applications in these sectors are on a rising trend. New and emerging applications should help developing countries by cost-effectively addressing some of the challenges to sustainable agricultural and irrigation development as well as food safety and food security. Examples of such applications are water purification systems to remove chemical and biological contaminants, rapid pathogen and chemical contaminant detection systems, and nano-enabled renewable energy technologies. In the immediate term, these applications are likely to come from research, development and innovation centres in the developed world. In the medium to longer term, developing countries will, hopefully, vigorously pursue indigenous programmes to develop these technologies. In many cases these countries already possess at least the rudiments of a knowledge infrastructure such as universities and research institutes.

2.3.2.2. Addressing poverty

Climate change poses an economic threat to all countries, but developing countries are the most vulnerable. It is estimated that they would bear 75–80% of the costs of damage. Even the minimum

[13] World Bank website, http://climatechange.worldbank.org/
[14] FAO–AGNS website, http://www.fao.org/ag/agn/agns/index_en.asp
[15] Woodrow Wilson International Centre for Scholars (2009), http://www.nanotechproject.org

possible warming the world is likely to experience—2 °C above preindustrial temperatures—could result in permanent reductions in GDP of 4–5% for Africa and South Asia.[5] Most developing countries lack sufficient financial and technical capacities to manage the increasing climate risk. Their income and prosperity also depends more directly on natural resources, which are sensitive to climate change, than developed countries while most, being in tropical and subtropical regions, already have a climate unsuited to conventional industrial development.

Economic growth alone is unlikely to be fast or equitable enough to counter threats from climate change, particularly if it remains tied to emissions and, therefore, would accelerate global warming while also providing the technical means to overcome it. Therefore, it would be wrong to frame the issue as a choice where growth and climate change adaptation are placed in opposition. An effective policy should attempt to combine enhancing development, reducing vulnerability and transitioning the economy to low-carbon growth paths. One way in which nanotechnology can help prevent climate-related economic collapse is by enabling entirely new industrial sectors to be established.

2.3.2.3. Disease prevention

The worldwide emergence of new diseases and the spreading of existing ones are expected as a further impact of climate change. This will be a consequence of the threats posed by climate change to food and water supplies, as well as the expected increase in poverty. Further risks are connected with the emergence of "ecological refugees", people displaced by climate change-related effects such as rising tides, wildfires, droughts and floods. The alteration of natural ecosystems and the northward shift of tropical diseases, the most prominent of which is malaria, will also contribute to this trend.

Nanotechnology is promising to be a useful tool, not only in mitigating the above causes of enhanced disease hazards, but also as a technology to be directly applied medically, in disease prevention and remediation. Nanotechnology-enhanced medicine boasts achievements such as cheap and portable biomedical analysis kits, enhanced drug delivery systems, efficient nanoparticle-based disinfectants incorporated in items for daily use and, prospectively, even nanoengineered antibacterial and antiviral agents.

2.3.2.4. Disaster management and environmental remediation

The development of environmental technologies and innovative solutions to prevent and remediate pollution is needed to ensure sustainable development. In 2007 the projected world market for the applications of environmental nanotechnologies was approximately \$6 billion (US) by 2010.[16] This market can be subdivided into four principal sectors: remediation, protection, maintenance and enhancement, of which remediation represents the fastest growing area, while maintenance and protection constitute the bulk of the remaining applications.

Various applications of nanotechnologies for environmental remediation have been successfully demonstrated at the laboratory scale but their efficacy and safety still have to be

[16] Report from the *JRC–Ispra Workshop on Nanotechnologies for Environmental Remediation*, Ispra, Italy (2007), http://www.nanowerk.com/nanotechnology/reports/reportpdf/report101.pdf

verified in the field. Conventional remediation technologies have so far shown only limited effectiveness in reducing pollutants levels and in responding to the challenges of major cleanup operations. Conventional filtration and purification plants used for supplying drinking water are generally only partially successful because of the limited efficacy of the active materials. Thanks to their much greater specific surface area, nanoparticles are much more effective as adsorption media than larger particles with the same chemical composition.

3. THE IMPACT OF NANOTECHNOLOGIES ON CLIMATE CHANGE

3.1. Nanotechnologies and applications

Nanostructured materials,[17] with dimensions (grain size, layer thickness or shapes) below 100 nm, are of increasing interest in nanotechnology, since they enable access to new ranges of electronic, magnetic, mechanical or optical properties in otherwise conventional materials. Polycrystalline materials with grain sizes less than a few nanometres have greatly altered properties compared to materials with larger grains, due to effects encountered at the grain boundaries. They typically exhibit increased strength; a property exploited in the development of highly wear-resistant coatings, for example.

Nanotechnology is best described as a "platform technology"[18] that will not by itself have a dramatic impact on climate change, but its incorporation into larger systems, such as those connected with the hydrogen-based economy, solar power technology or next-generation batteries, could have a profound impact on energy consumption and, hence, on greenhouse gas emissions.

There are many ways to view the effect of nanotechnology applications on climate change. One is to follow the energy supply chain and observe the manner in which clean nanotechnologies supplant old technologies based on the carbon fossil fuel cycle (Table 1). This way is very helpful in discerning the synergetic effects of multiple technologies applied in parallel inside a comprehensive conservation reuse and reduction framework.

Table 1. The sectors affected by nanotechnology arranged by position in the energy supply chain.

Energy sources	Energy change	Energy distribution	Energy storage	Energy usage
Photovoltaics	Gas turbines	Power transmission	Batteries	Thermal insulation
Wind energy	Fuel cells	Smart grids	Supercapacitors	Air conditioning
Geothermal	Combustion engines	Superconducting power lines	Hydrogen storage	Lightweight construction
Hydro/tidal power	Electric motors	Wireless power transmission	Thermal energy storage	Industrial processes
Biomass	Thermoelectrics	Heat transfer	Fuel refining	Lighting

Another is to focus on key technology areas where research and development (R & D) is funded in tandem. This allows pinpointing the fields where nanotechnology development can gather momentum. One aims to then quantify the expected energy/emissions savings as well as

[17] A.G. Mamalis, L.O.G. Vogtländer, A. Markopoulos, Nanotechnology and nanostructured materials: trends in carbon nanotubes. *Precision Engineering* **28** (2004) 16–30.

[18] B. Walsh, *Environmentally Beneficial Nanotechnologies: Barriers and Opportunities*. Oakdene Hollins for DEFRA Report (2007).

the technology's maturity and probability of success. Five such areas have been identified in recent technology reports (Table 2, taken from ref.18).

Table 2. Summary of the potential of nanotechnologies for climate change mitigation in the UK.[18]

Application	Impact of nanotechnol in the area	Infrastructural changes required	Benefit (Mte[a] CO_2 per annum)	Implementation timescale (yrs)
Fuel efficiency	Critical	Low	< 3	< 5
Insulation	Moderate	Low	< 3	3–8
Photovoltaics	High	Moderate	~6	> 5
Electricity storage	High	High	10–42	10–40
Hydrogen economy	Critical	Very high	29–120	20–40

[a] Megatonne-equivalents

Finally, the effects can be categorized based on the way in which a specific nanotechnology is utilized. The more mature nanotechnology applications invariably involve nanomaterials used in bulk structures or on surfaces (nanocoatings, nanoparticles, nanotubes, aerogels etc.). Another application involves nanoengineered surfaces involved in microscopic phenomena (nanocatalysts, nanomembranes) and nanomaterials of biological origin or interacting with living organisms. A further developing sector of nanotechnology is the miniaturization (nanification) of functions already available in MEMS/NEMS applications.

3.2. The energy supply chain

Nanotechnology has the opportunity to contribute in several ways to the problem of energy supply, which can be succinctly expressed as the current undersupply of usable energy and the trend for the gap to get worse. The principal near-term technical impacts of nanotechnology are considered in the following.

3.2.1. Renewable energies

3.2.1.1. Photovoltaics and solar energy

There is expected to be direct impact on photovoltaic cells. The main primary obstacle to the widespread deployment of photovoltaics is the high cost of conventional cells. Current solar cell technologies are mainly based on silicon (single-crystal or polycrystalline). However, they are expensive to manufacture and have limited efficiency. A low-cost alternative is organic polymer-based thin film solar cells, based on nanoparticles and polymers. These are now being used to manufacture flexible solar panels. The thin film technology is cost-effective for three reasons: First, it uses a cheap polymer substrate coated by a thin film of an active component, comprising either amorphous silicon or nanoscaled CdS, CdSe, CdTe, TiO_2, ZnO, other quantum dots, organic materials or other compounds. Second, the material requirement (i.e., the amount) is much less than in the case of silicon wafers. Third, the flexible substrate technology enables the use of continuous roll processing techniques, rather than the step (batch) technique used in semiconductor plants; this alone results in dramatic cost reductions.

Devices incorporating particles (e.g., Grätzel cells) offer potentially much lower fabrication costs than those based on machined sheets. The potential of incorporating further complexity through mimicry of natural photosynthesis, the original inspiration for the Grätzel cell, is not yet exhausted. The main secondary obstacle is that except for a few specialized applications (such as powering air-conditioners in Arabia) the electricity thus generated needs to be stored, hence the interest in simultaneous conversion and storage. Undoubtedly natural photosynthesis is only possible through an exact arrangement of atoms within the photosystems working within plant cells, and the more precisely artificial light harvesters can be assembled, the more successful they are likely to be. The eutactic environment of the nanofacturing paradigm is likely to be especially powerful for achieving the required exactness.

3.2.1.2. Wind energy

The recent trend of increasingly larger and more powerful wind generators poses great challenges for the mechanical load capacity of materials and components.[19] Well able to cope with such demands, the application of nanotechnologies could lead to a new generation of superior component designs. Especially significant is the development of composite materials based on carbon nanotubes for lightweight and high-strength rotor blades and also to help prevent failures from lightning strikes, by providing grounding and electromagnetic shielding. Beyond that, biomimetic surfaces can increase areodynamic efficiency and decrease noise; shafts and bearings can be coated with ultrahard materials to reduce friction and wear; and so forth.

3.2.1.3. Thermoelectric energy conversion

Thermoelectric generators will see many applications in the future, as we strive to recycle the wasted thermal energy from combustion engines, as well as industrial and residential uses. Before this happens, their currently low efficiency has to be increased and their weight and cost reduced. Nanostructured thermoelectrics are of great interest since the electrical and thermal properties of the materials can be specifically influenced by the substructure, enabling enhanced performance informed by fundamental knowledge of the phenomena, translated into atomically precise engineering. Although atom-by-atom assembly is not yet industrially feasible, it may already be possible to exploit extant nanostructured surfaces, quantum dots and quantum wires; materials of interest are cobaltates, tellurides and skutterudites.[19]

3.2.2. Fuel cells and the hydrogen economy

Although the scientific basis of this technology, whereby fuel is converted to electricity directly, was established over 150 years by Christian Schönbein in Basel it has been very slow to become established. Fuel cells represent a key enabling technology for renewable energy systems, thanks to their high energy conversion efficiency, approaching 60% (compared to 25% efficiency for the best gasoline engines), and for being pollution-free, since if fuelled by hydrogen they produce only water (steam) as exhaust.

[19] Hessian Ministry of the Economy, Transport, and Urban and Regional Development, Report: *Application of Nanotechnologies to the Energy Sector* (2008), p. 40.

3.2.2.1. Fuel cell fabrication

As with photovoltaic cells, the main primary obstacle is the high cost of fabrication. Nanotechnology is expected to contribute through miniaturization (nanification) of all components (especially reducing the thickness of the various laminar elements), simultaneously reducing inefficiencies and costs, and through realizing better catalysts for oxygen reduction and fuel oxidation. The membrane separating the two electrodes is an important component of a fuel cell, allowing only the hydrogen ions to pass through towards the cathode. Nano-engineered membranes in fuel cells are more efficient, enabling the manufacture of more lightweight and longer lasting fuel cells. Another particular priority is developing fuel cells able to use feedstocks other than hydrogen.

3.2.2.2. Hydrogen production

Currently, the most economical way to produce hydrogen is from natural gas; however, it leads to greenhouse gas emissions. The best "clean" approach to generate hydrogen is by photocatalytic splitting of water molecules into hydrogen and oxygen atoms using sunlight. This is the classical Fujishima–Honda approach. Hydrogen has been produced with this technique with an efficiency of 60%, employing a new system consisting of a gold electrode covered with a layer structure of InP nanoparticles intermixed with an iron-sulfur complex. Another "clean" process for hydrogen production is the electrolysis of water, as long as the sources of electricity are renewable. Electrodes coated with nano Ni–Fe alloy increase hydrogen gas output by 300% (compared with uncoated electrodes) at 85% efficiency, rendering this process commercially viable.

3.2.2.3. Hydrogen storage

However the hydrogen is generated, it needs to be stored and doing this efficiently is still problematical. Nanotechnology will be important in addressing this problem as well. Promising candidates are "molecular labyrinths"—nanostructured material systems like carbon nanotubes (CNTs), alanates, nanoMg-based hydrides, complex hydride/carbon nanocomposites, boron nitride nanotubes, TiS_2/MoS_2 nanotubes and polymer nanocomposites. It is worth noting the development of metal–organic framework (MOF) compounds, comprising metal oxide clusters connected by organic linkages. These are ideal for hydrogen storage because of their tunable pore size and functionality, high surface area, low density, and both thermal and mechanical stability. Through the design and fabrication of rational storage matrix materials, nanotechnology should be able to contribute to effective storage, although whether this will tip the balance in favour of the hydrogen economy is still questionable.

3.2.3. Energy storage

The primary means of storing energy is as fuel, but unless photoelectrochemical cells generating fuel from sunlight receive renewed impetus, renewable sources will mainly produce electricity and except for some special cases at least some of the electricity will have to be stored to enable the supply to match demand.

3.2.3.1. Batteries

Electric and hybrid cars have the potential to dramatically reduce the emissions that cause both global warming and local air pollution. In addition, they help to curb the world's dependence on oil. According to estimates,[20] electric vehicles would reduce GHG emissions by 26% compared with gasoline-powered vehicles, with a concomitant transformation of the automotive industry. Nanotechnology is promising to improve the performance and lifetimes of the popular Li-ion batteries, to enhance their energy and power densities and shorten recharge time, as well as decrease their size and weight while improving safety and stability, through rationally optimized electrode materials and electrolytes. Anodes and cathodes with higher loading and discharge capacities and yielding higher cell voltages are researched for increasing storage capacity; polymer electrolytes and thin-film ceramic separators are researched for increasing safety.

3.2.3.2. Supercapacitors

Automakers are exploring the concept of combining supercapacitors with Li-ion batteries as the next generation energy storage system for their electric hybrid vehicles. Although the energy density of capacitors is quite low compared to batteries, their excellent power characteristics are very attractive; at the very least they could be used to provide short bursts of power and can assist highway acceleration, hill climbing, braking or cold starting, thereby preserving the main battery's life. The addition of supercapacitors can help the new generation of cars to accelerate at comparable or better rates than traditional petrol-only engine vehicles, while achieving significantly reduced fuel consumption. Recently, there has been progress in enhancing their performance with the help of nanotechnology. Supercapacitors based on graphene and carbon nanotubes have attracted interest,[21] although in this particular case the impact of nanotechnology is likely to be small since using ordinary (and much cheaper) carbon black has already enabled over 90% of the theoretical maximum charge storage capacity to be achieved.

3.2.4. Energy conversion efficiency

This heading comprises a very heterogeneous collection of technical impacts, centred around making the primary uses of energy (i.e., transportation, heating and lighting) more efficient.

3.2.4.1. Weight reduction

The use of lighter, stronger and stiffer nanocomposite materials has the potential to significantly reduce dead weight and thereby promote energy efficiency in transportation. Promising candidate materials in this area are polymers—thermosets, thermoplastics and elastomers—reinforced with colloidal silica, nanoclays and nanotubes. The use of nanocomposites can lead

[20] A. Elgowainy, A. Burnham, M. Wang, J. Molburg, A. Rousseau, *Well-to-Wheels Energy Use and Greenhouse Gas Emissions Analysis of Plug-in Hybrid Electric Vehicles*. Argonne National Laboratory Report (2009).

[21] J. Yan, T. Wei, B. Shao, Z. Fan, W. Qian, M. Zhang, F. Wei, Preparation of graphene nanosheet/carbon nanotube/polyaniline composite as electrode material for supercapacitors. *Journal of Power Sources* **195** (2010) 3041–3045.

to reduced energy consumption in cars, while the impact in the aerospace sector will likely be even more dramatic. It is estimated[22] that use of CNT-reinforced polymer composite airframes in place of aluminum airframes would result in a 14% decrease in the structural mass of aircraft, with a concomitant reduction in fuel consumption of about 10%.

3.2.4.2. Efficiency in combustion and electric engines

Nanocatalysts used as fuel additives can help increase fuel efficiency and reduce emissions of conventional internal combustion engines. Cerium oxide powders and cerium salts are being researched. Enercat, developed by Energenics,[23] is a third generation nanocatalyst, which uses oxygen-storing cerium oxide nanoparticles to promote complete fuel combustion, which obviously reduces fuel consumption for a given output of mechanical energy.

Nanostructured coatings with very low coefficients of friction and extremely good wear resistance will find application in all moving machinery, improving its efficiency (i.e., reducing the energy required to achieve a given result). Examples include electricity-generating wind turbines and electric motors. Nano-based lubricants and nanocoatings can significantly reduce the coefficient of friction in engine and drive train components and are being increasingly introduced into the market. Reducing friction can typically lower fuel consumption by 2%.[24] The lubricant materials being researched are layered inorganic compounds like WS_2, MoS_2, NbS_2 etc., as well as hard particles like monocrystalline diamond powder (MCDP) and nanoboron for incorporation into the surfaces in relative motion.

Nanoparticle-based ceramic antiadhesive coatings can be applied to boilers and heat exchangers to considerably reduce caking, thereby increasing their operating life and thermal efficiency. Nanostructured thermal barrier layers for gas turbine blades allow turbines to operate at higher temperatures, increasing fuel efficiency; nanostructured multilayer coatings applied with ultraprecision plasma deposition technologies can result in coatings with exceptionally low coefficients of thermal conductivity and thermal expansion. According to calculations of the IFW Darmstadt, fuel savings of about 1 Meuro could be achieved annually through an efficiency increase of 1% for a single 400 MW gas and steam turbine power plant.[19]

Nanostructured magnetic materials will help increase the efficiency of electric motors and transformers (and the dynamos used in windmills and water turbines) by developing cores with higher magnetic permeability and stronger permanent magnets.

3.2.4.3. Energy transport

Increasing the efficiency of the electricity grid is largely dependent on the development of power electronics to ensure low loss conversion and control of electricity as it is transmitted between the production site and the end user. This will become specially important in a setting of distributed and intermittent power generation from sources like photovoltaics and wind farms. The development of power electronics can benefit from nanotechnologies, for example

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[22] S.E. O' Donell, Impact of Nanomaterials in Airframes on Commercial Aviation, MITRE Corp–AIAA research white paper.
[23] Cerion Enterprises website, http://www.cerionenterprises.com
[24] Applied Nanosurfaces website, http://www.appliednanosurfaces.com/offering.html

through the optimization of the layer design of wide band-gap semiconductors or through the application of nanotubes.

For a further leap in power transmission technology, cheap, reliable and efficient materials for superconducting cables and electronics, such as circuit breakers and transformers, have to be developed. The critical current density of a superconducting cable is dependent on the size and number of defects. Efficient precursor materials for both the superconductor and insulating layers, based on thin-film deposition techniques or on nanoparticle consolidation, will help produce low-cost multifilament wires capable of conveying a high current density. In the future, carbon nanotubes may be likewise employed.

3.2.4.4. Efficient lighting

For all applications where collateral heat production is not required, nanotechnology-enabled light-emitting diodes can replace incandescent filaments. They can achieve a similar luminous output for much less input power than incandescent lamps. The heat produced by the latter may be of value in a domestic context (e.g., contributing to space heating in winter) but it is simply wasted in the case of outdoor street lighting (although the aesthetic effect is very agreeable, which is not a negligible consideration; quite a few streets in London are still lit by gas lights for the same reason). It should be borne in mind that the actual operational efficiency of a device in a given functional context typically represents only a fraction of the overall effectiveness in achieving the intended function. For example, if the intended function of street lighting is to reduce road accidents, there is probably an ergonomic limit of the number of lamps per unit length of street above which the reduction becomes insignificant. It is quite plausible to suggest that a 50% reduction in the number of lamps could be effected without diminution of the functional effect. Such a reduction would be equivalent to a really significant advance in the device technology applied to an undiminished number of lamps.

3.2.4.5. Heating and insulation

Air conditioning for buildings can be made more efficient than traditional installations with the use of nanostructured phase change materials in construction.[25] Paraffin microcapsules can be employed to absorb latent heat during the day by melting and emit it during the night by solidifying. Microencapsulation offers a number of advantages: no wax can leak out, while the large surface areas and small volumes of the capsules allow increased heat absorption/release rates. A thin layer of such material can offer the same heat capacity as a thick concrete wall, enabling energy-efficient lightweight construction.

Highly porous nanostructured materials, such as aerogels, could greatly reduce heat transfer through building elements and assist in reducing heating loads placed on air conditioning/heating systems. An aerogel is a nanoporous superinsulating material having an extremely low density (90–95% is air). Silica aerogels are the lightest solid materials known (density < 0.05 g/cm^3) with excellent thermal insulating properties, high temperature stability, very low dielectric constant and high surface area. Aerogels are a breakthrough materials

[25] Microcapsules to combat climate change (2009), http://www.nanowerk.com/news/newsid=14181.php

technology for energy-conserving buildings, but their present high cost is inhibiting their widespread adoption. Hence, there is intense interest in developing mass production; novel techniques, such as using silica-rich rice husks (agricultural waste) as the feedstock,[26] could reduce the production cost of aerogels by 80%.

3.2.5. Resource extraction

Current technologies used to extract metal from ores use vastly more energy than is theoretically required. Nanotechnology can be brought to bear on this problem in many different ways. Biomimicry seems an especially attractive route to explore since living organisms are extremely good at extracting very dilute raw materials from their environment in order to make things (such as a skeleton). They operate at room temperature and, seemingly, close to the thermodynamic limit. Bio-inspired nanotechnology will, hopefully, enable us to mimic devices like the kidneys using robust, artificial materials.

3.2.6. Localized manufacture

Once the stage of the personal nanofactory has been reached, possibly the greatest and ultimate contribution of nanotechnology to energy conservation will be through the great diminution of the need to transport raw materials and finished products around the world. The amount of energy currently consumed by transport in one form or another is estimated at 30–70% of total energy consumption. A reduction in absolute terms to 5–10% of its present value seems a not unrealistic target—with many collateral environmental benefits.

3.3. Other mitigation techniques

3.3.1. Nanotechnologies and CCS

Nano-optimized membranes are being developed for direct CO_2 scrubbing at fossil fuel power plants.[27, 28] Porifera, Inc. aims to develop high flux, high selectivity carbon nanotube membranes.[29] Two projects by GATech[30] utilize the high specific surface area of hollow fibres: hollow-fibre composite membranes using nanoporous metalorganic framework materials to separate carbon dioxide from the flue gases; and hollow-fibre sorbents to soak up carbon dioxide "like a sponge"—and then release it when heated. A team at Pacific Northwest National Laboratory (PNNL) has created a new series of materials based on metalorganic frameworks (MOFs) that possess tiny cages, trapping CO_2 before it reaches the atmosphere. The cages themselves consist of metal ions linked together with organic ligands forming a porous network .[31]

[26] H. Hamdan, *Improvements in Silica Aerogels*, European Patent Application EP1689676 (2006).
[27] Nanowerk.com, New membranes design will improve carbon dioxide capture (2008), http://www.nanowerk.com/news/newsid=4452.php
[28] US Department of Energy, Advanced Research Projects Agency (ARPA-E), http://arpa-e.energy.gov/ProgramsProjects/Programs.aspx
[29] Porifera, Inc. website, http://www.poriferanano.com
[30] GATech website, http://www.nano.gatech.edu/news/release.php?id=5083
[31] P.K. Thallapally et al., Flexible (breathing) interpenetrated metal-organic frameworks for CO_2 separation applications. *J. Am. Chem. Soc.* **130** (2008) 16842–16843.

3.3.2. Nanotechnologies and climate engineering

There is heightened interest in the use of nanomaterials in climate engineering. By injecting aerosols into the upper atmosphere, the scattering of incident sunlight can be enhanced so as to produce a cooling tendency. This is one example of how it might be possible to engineer the climate and mitigate the effect of GHG accumulation.[32] To date, climate engineering studies have focused on sulfate aerosols. Engineered nanoparticles could exploit *photophoresis*—the natural tendency of particles to migrate when suspended colloidally inside a fluid and illuminated by light. That would enable more control over particle distribution and lifetime than is possible with sulfates, perhaps greatly alleviating the side effects regarding which climate engineering efforts on a massive scale must always be vigilant. The use of electrostatic or magnetic materials enables the exploitation of photophoretic forces not found in nature. Furthermore, photophoretic levitation could loft particles above the stratosphere, reducing their capacity to interfere with ozone; and, by increasing particle lifetimes, reduced aerosol quantities would be required. Moreover, particles could be engineered to drift towards the Earth's poles, enabling albedo modification to be tailored to counter polar warming, which has more pronounced ecological effects, while minimizing the impact on equatorial regions.

3.4. Technical literacy and political momentum

The real benefits of nanotechnology (which, by changing the way we understand technology and science will also impact on the way we understand our relationship with the rest of the universe) can probably only be realized if there is a significant—at least tenfold—increase in the technical literacy of the general population. Technical literacy means the ability to understand an intelligible account of the technology (that is, an account in plain language not requiring any prior specialized knowledge). It would be tragic if nanotechnology remains—like so many technologies today—a mysterious, impenetrable black box. Perhaps a good way of measuring technical literacy is to compare the space in popular media (newspapers, television broadcasts) devoted to technical topics relative to, say, sport. Once equality is reached, in any democratic society political momentum will then inevitably accrue. An early indication of this could be that the often elliptical pronouncements of government chief scientific advisers (who are typically plucked from academic obscurity to occupy a position of considerable political influence) will be subjected to intense scrutiny and criticism rather than, as at present, being considered as oracles.

4. DISCUSSION

In an attempt to provide guidance for policymakers, many international organizations and "think thanks" have undertaken meticulous studies[1, 5, 18] to predict the course of the climate change mitigation and adaptation efforts. In the following, we review some of the findings and add our own assessment.

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[32] D.W. Keith, Photophoretic levitation of engineered aerosols for geoengineering. *Proc. Natl Acad. Sci. USA* **107** (2010) 16428–16431.

4.1. The contribution of various technology sectors to GHG emissions savings

Large uncertainties are involved in predicting the future contributions of different technologies. However, all stabilization scenarios agree that 60 to 80% of the reductions over the course of the present century would come from the energy sector and industry. Including mitigation options for other GHGs in addition to CO_2 and considering land-use and forestry provide greater flexibility and cost-effectiveness. Energy efficiency is a central issue across many scenarios for most regions and time scales. For lower GHG stabilization levels, scenarios necessarily put more emphasis on the use of low-carbon energy sources, such as renewable energy or nuclear power, and on the use of CCS. But any improvements would need to be much faster than in the past.[33]

Any estimates of mitigation costs and potentials have to depend on assumptions about future socio-economic growth, technological change and consumption patterns. One particularly uncertain feature is the assumptions made about the drivers of technology diffusion and the potential of long-term technology performance and cost improvements. Also, little is known about the effects of such widespread changes on human behaviour and lifestyles.[34]

4.2. The ability of developing countries to adopt new technologies

To achieve the 2 °C global temperature trajectory, which would stabilize the climate in a best-case scenario, developing countries would have to embark on an entirely different technology path than that on which developed countries have been until now. There is a disparity between energy and emissions growth, projected to come largely from developing countries, and investment in clean energy technology, which takes place mainly in developed countries.

New technologies, such as wind energy, have been traditionally prototyped first in developed economies, followed by commercial roll-outs in developing countries. However, large-scale demonstrations of advanced technologies would need to be introduced now, in parallel, in both developed and developing countries, in order to keep up with the goal of the 2 °C trajectory and an emissions peak in 10 years. This change is starting to be seen with the rapid advent of research and development in Brazil, China, India, and a few other technology leaders in the developing world. The lowest-cost manufacturers for key technologies like solar cells, efficient lighting and ethanol are all in developing countries. Nanotechnology, however, is still missing from this picture, because research and development in this sector has been seen as a means for developed countries to press their competitive technological edge in sectors other than energy.

One of the major barriers that developing countries are facing is the high incremental cost of developing and demonstrating advanced clean energy technologies. Developed countries would have to substantially increase financial assistance and encourage low-carbon technology transfers to the developing world through mechanisms such as a global technology fund.[35] In the area of nanotechnology, this would require declassifying and decoupling advances in nanotechnology from the military sector. The alternative is for the developing countries to

[33] IPCC, *AR4 Synthesis Report* (2007). §5.5: Technology flows and development (p. 68).
[34] IPCC, *AR4 Synthesis Report* (2007). §5.6: Costs of mitigation and long-term stabilisation targets (p. 73).
[35] World Bank, *World Development Report*, Chapter 4: Energizing development without compromising the climate (2010) pp. 220–221.

unlock their latent intellectual resources (including their citizens who have studied in the developed world) and develop the required technologies themselves.

4.3. Detractors

The main voices of scepticism against the wholesale adoption of nanotechnology in the fight against climate change come from environmental organizations.[36] They are centred on the environmental and health impacts of unleashing nanomaterials into the environment as well as the eventual effectiveness of nanotechnology in actually curbing energy use and GHG emissions.

4.3.1. Environmental impacts

It has often been stated that nanotechnology will enable the environment to be returned to a pristine state, without explaining the process by which that might be achieved. It seems that there are going to be three principal impacts of nanotechnology on the environment. The first is immediate and direct and concerns the use of nanoparticles for environmental remediation. The second is long-term and indirect and is the corollary of atomically precise technologies, which by definition eliminate waste, since only the atoms needed in the final product are used. This applies not only to the actual fabrication of artefacts for human use, but also to the extraction of chemical elements from the geosphere (should those elements still be necessary). The third is a further corollary of localized fabrication (i.e., when productive nanosystems and personal nanofactories are widely deployed)—almost all of the currently vast land, sea and air traffic involved in wholesale and retail distribution should be eliminated. The nanofactories would include nano-engineered "artificial kidneys" used to extract desirable elements from very dilute sources, such as seawater, as well as to extract elements and extractable compounds from natural water polluted with them.

Micromanufacturing (semiconductor processing) has higher environmental demands than manufacturing with conventional materials. It is characterized by the very high use of water and organic solvents, hence large quantities of hazardous substances are used or generated as by-products. Only 0.1% of the materials used to manufacture the microproducts found in computers and electronic goods are contained in the final products—the remaining 99.9% becomes waste. And the basic material used is silicon, the refining of which generates large quantities of GHG.[2]

When the scale of manufacture is further shrunk to the nanoscale (i.e., feature sizes below 100 nm, as in the current generation of very large scale integrated circuits) this situation is exacerbated. Furthermore, there is a growing body of research demonstrating that there may be health and environmental risks associated with some of the special nanomaterials used in energy generation, storage and efficiency applications. For example, some kinds of nanotubes can cause mesothelioma, the deadly cancer associated with asbestos exposure.

The release of nanomaterials produced for other purposes (i.e., not for remediation) to the environment could result in accelerated generation of potent GHG emissions. For example, antibacterial nanosilver is now widely used in clothing, textiles, cleaning products, personal care products and surface coatings and quantities of it are bound to end up in waste water. When

[36] Friends of the Earth. Nanotechnology, climate and energy: Over-heated promises and hot air? (2010) http://www.foe.org/nano-climate

nanosilver is present in sewage treatment sludge, four times the typical level of nitrous oxide, a potent GHG, is released.

In summary, the significant environmental benefits of nanotechnology will only be realized when the era of productive nanosystems (the personal nanofactory) arrives. Until then, we have a kind of unauthentic nanotechnology consisting mainly of the incorporation of true nano-objects (the making of which costs a great deal of energy and generates a great deal of waste) in an atomically imprecise fashion in a matrix. Almost certainly it is necessary to traverse this stage before arriving at authentic, atomically precise nanotechnology, but during the intermediate stage one must be careful not to make exaggerated claims about the benefits.

4.3.2. Contested effectiveness

Manufacturing carbon nanofibres requires 13–50 times the energy per unit of *mass* required for aluminium, and 95–360 times the energy for making steel. Single-walled carbon nanotubes may be one of the most energy-intensively manufactured materials known to man. Therefore, due to the large energy demands of manufacturing nanomaterials, some applications of nanotechnology in the energy sector may end up incurring a net energy cost, instead of saving energy. For example, even though strengthening windmill blades with carbon nanofibres would make the blades lighter, because of the energy required to manufacture the nanoblades, early life cycle analysis shows that it could be more energy-efficient to use conventional blades.

Nanotechnology advances in the hydrogen sector are at a very early stage. It is improbable that hydrogen generated using renewable energy will be widely adopted in transportation soon enough—in the next ten or twenty years, which are critical for emissions cuts.

Most nanoproducts are not designed for the energy sector and will come at a net energy cost. Applied without deliberation, such nanoproducts may greatly and negatively overshadow those applications where nanotechnology could deliver net energy savings.

4.4. Further considerations

From the above discussion the following need to be further considered:[37]

- Is enough effort being made to utilize renewable sources and mitigate oil consumption? What should be the areas of priority investment?
- How long will it take for nanotechnologies bringing decisive emissions reductions to be widely adopted?
- How might nanotechnology advances be freely shared with developing countries to decrease their dependence on fossil fuels?
- Will the use of key chemical elements in nanomaterials be unsustainable and create a shortage of certain raw materials (e.g., indium, gallium, platinum)?
- How can we ensure that materials/devices incorporating nanotechnology advances do in fact have a smaller environmental footprint than existing technologies?

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[37] *Nano and the Environment*, report from the workshop organized by Nanoforum and the Institute for Environment and Sustainability (JRC Ispra) (2006) p. 17. http://www.nanowerk.com/nanotechnology/reports/reportpdf/report75.pdf

5. CONCLUDING REMARKS

- Nanotechnology can primarily help to mitigate and adapt to climate change by increasing energy efficiency in a great variety of ways, at each stage of the energy supply chain.
- The "nano" economic model implies much less transport, which is one of the main contributors to global warming.
- By increasing the efficiency of agriculture, it should also remove the need to convert tropical rainforests into farmland, which is the biggest single contributor to global warming.
- Nanotechnology should encourage the growth of technical literacy. A knowledgeable population is the best guarantor of future climate stability.
- The adaptation strategy can find pivotal support from nanotechnology applications not related to the energy sector, but connected with food and water quality as well as health and disease prevention.
- It is crucial for the mitigation strategy to facilitate the quick and widespread adoption of promising nanotechnologies by developing countries.
- Nanotechnologies need to prove that they provide net energy savings, do not strain scarce natural resources and do not pose new environmental risks before they are used in the world-changing scale that is required for creating a technological arsenal to combat climate change.