Nanotechnology, climate and energy: over-heated promises and hot air?

Friends of the Earth

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"Very few people have looked beyond the shiny promise of nanotechnology to try and understand how this far-reaching new technique is actually developing. This report is an excellent glimpse inside, and it offers a judicious and balanced account of a subject we need very much to be thinking about."

– Bill McKibben, author, environmentalist, founder 350.org

Friends of the Earth

UK Edition

A report prepared for Friends of the Earth Australia, Friends of the Earth England, Wales, and Northern Ireland (EWNI), Friends of the Earth Europe and Friends of the Earth United States November 2010.

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Table of Contents

executive summary

In a world increasingly concerned about climate change, resource depletion, pollution and water shortages, nanotechnology has been much heralded as a new environmental saviour. Proponents have claimed that nanotechnology will deliver energy technologies that are efficient, inexpensive and environmentally sound. They predict that highly precise nanomanufacturing and the use of smaller quantities of potent nanomaterials will break the tie between economic activity and resource use. In short, it is argued that nanotechnology will enable ongoing economic growth and the expansion of consumer culture at a vastly reduced environmental cost.

In this report, for the first time, Friends of the Earth puts the 'green' claims of industry under the microscope. Our investigation reveals that the nanotechnology industry has over-promised and under-delivered. Many of the claims made regarding nanotechnology's environmental performance, and breakthroughs touted by companies claiming to be near market, are not matched by reality. Worse, the energy and environmental costs of the growing nano industry are far higher than expected.

We also reveal that despite their green rhetoric, governments in the United States, Australia, the United Kingdom, Mexico, Japan and Saudi Arabia are using public funds to develop nanotechnology to find and extract more oil and gas. The world's biggest petrochemical companies, including Halliburton, Shell, BP America, Exxon Mobil and Petrobras have established a joint consortium to fund research to increase oil extraction.

The performance of nano-based renewables has been considerably less than predicted. Efficiency of solar energy conversion by nano solar panels is still about 10 percent behind that achieved by silicon panels. The technical challenges of bringing renewable energy laboratory achievements to market have been prohibitive in many instances. The United States President's Council of Advisors on Science and Technology states that in 2009 only one percent of global nanotechnology-based products came from the energy and environmental sector.

The energy demands and environmental impacts of manufacturing nanomaterials are unexpectedly high. Manufacturing carbon nanofibers requires 13 to 50 times the energy required to manufacture smelting aluminium, and 95-360 times the energy to make steel, on an equal mass basis. A team of United States researchers has concluded that single walled carbon nanotubes may be "one of the most energy intensive materials known to humankind".

Due to the large energy demands of manufacturing nanomaterials, even some nano applications in the energy saving sector will come at a net energy cost. For example even though strengthening windmill blades with carbon nanofibers 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 windmill blades.

Much-touted nano developments in the hydrogen sector are at a very early stage. It is improbable that cars powered by renewable energy generated hydrogen will be on the roads in the next ten or twenty years – the period in which emissions cuts are critical. In the meantime, development of hydrogen cars entrenches reliance on fossil fuels to produce the hydrogen.

Most nanoproducts are not designed for the energy sector and will come at a net energy cost. Super strong nano golf clubs, wrinkle disguising nanocosmetics, and colour-enhanced television screens take a large quantity of energy to produce, while offering no environmental savings. Such nanoproducts greatly outnumber applications in which nano could deliver net energy savings.

The environmental demands of nanomanufacturing are higher than that of conventional materials. Nanomanufacturing is characterised by very high use of water and solvents. Large quantities of hazardous substances are used or generated as byproducts. Only one tenth of one percent of materials used to manufacture nanoproducts found in computers and electronic goods are contained in the final products. That is, 99.9 percent of materials used in manufacturing become waste products.

Despite the serious uncertainties, there is a growing body of research demonstrating that some nanomaterials used in energy generation, storage and efficiency applications can pose health and environmental risks. Carbon nanotubes are touted for use in electronics, energy applications, and specialty car and plane parts. However, early research shows that some forms of nanotubes can cause mesothelioma, the deadly cancer associated with asbestos exposure.

The release of nanomaterials to the environment could also result in accelerated generation of potent greenhouse gas emissions. Antibacterial nano silver is used widely in clothing, textiles, cleaning products, personal care products and surface coatings. Yet preliminary study shows that when nano silver is exposed to sludge, similar to that found in typical waste water treatment plants, four times the typical level of the potent greenhouse gas nitrous oxide is released.

> ***Nanotechnology is not an unqualified environmental saviour nor will its widespread use in everything from socks to face creams enable us to pursue 'business as usual' while substantively reducing our environmental footprint.***

Nanotechnology is not an unqualified environmental saviour nor will its widespread use in everything from socks to face creams enable us to pursue 'business as usual' while substantively reducing our environmental footprint. At best, such claims can be interpreted as the result of wishful thinking on the part of proponents; at worst they can be seen as misleading greenwash.

Nanotechnology is a powerful technology that has the potential to deliver novel approaches to the methods by which we harness, use, and store energy. Nevertheless, Friends of the Earth warns that overall, this technology will come at a huge energy and broader environmental cost. Nanotechnology may ultimately facilitate the next wave of expansion of the global economy, deepening our reliance on fossil fuels and existing hazardous chemicals, while introducing a new generation of hazards. Further, it may transform and integrate ever-more parts of nature into our systems of production and consumption.

Wasteful and inequitable consumption and production has had a devastating environmental impact (UNEP 2010). Desertification, salinity, polluted air and soils, lack of potable water, huge losses to biodiversity, plummeting fish stocks, and increasing competition for arable land between buildings, food crops and biofuels characterise the first decade of the 21st century.

At the same time as ecological systems and services have been stretched to a breaking point, economic inequity between the global rich and global poor has widened.[1] The years 2008 and 2009 saw the worst world food crisis ever. Despite decades of medical breakthroughs, between 1.7 and 2 billion people worldwide have inadequate or no access to life-saving basic medicines (UN Millennium Project 2005).

Climate change and global warming have been viewed as the meta problem, "the defining human development issue of our generation" (UNDP 2007, 1). If left unchecked, climate change is predicted to promote greater ocean acidification, loss of species, loss of arable crop land, and diminished fresh water resources. At the same time, more extreme weather events, crop failures and rising ocean levels may create a new wave of environmental refugees and shifting patterns of disease. The world's poorest people will disproportionately bear the negative impacts of these changes (UNDP 2007).

The United States (US) National Aeronautics and Space Administration (NASA) has already reported the effects of global climate change on the environment. According to NASA,

> *"Glaciers have shrunk, ice on rivers and lakes is breaking up earlier, plant and animal ranges have shifted and trees are flowering sooner. Effects that scientists had predicted in the past would result from global climate change are now occurring: loss of sea ice, accelerated sea level rise and longer, more intense heat waves" (NASA n.d.).*

The International Panel on Climate Change (IPCC) has advised that for a 46 percent chance of stabilising temperature rises below 2°C, the point at which major melting of sea ice and a 'domino effect' of warming could occur, greenhouse gas (GHG) emissions from Annex-I (industrialised) countries must fall by 25–40 percent on 1990 levels by 2020, and must fall by 85-90 percent by 2050 (Chapter 13, Box 13.7; IPCC AR4 WGIII 2007). Even using the IPCC's assumptions, which

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[1] *The gap between the global rich and the global poor is growing, although by some measures economic inequality between countries is decreasing. Milanovic (2005, cited in Cozzens et al. 2008) has examined global data, and concludes that inequality between countries' gross domestic product (GDP) per capita is rising. If GDP is weighted by population, inequality between countries is declining. Nonetheless, data analyzed by Milanovic and others demonstrate that inequality within countries is increasing.*

have been criticised by environmentalists as unreasonably conservative, this dramatic reduction in greenhouse gas emissions delivers only roughly even odds that global temperatures will not rise above 2°C (Spratt 2009; Zhou 2009).

Governments around the world have struggled to agree on policy targets for greenhouse gas reductions commensurate with recommendations from the IPCC, while industry has struggled to find new economic opportunities in a potentially carbon-restricted future marketplace. Renewed attention has been focused on the technology sector to deliver 'drop in' substitute energy, services, and goods that achieve emissions savings without requiring the public or industry to modify behaviour, consumption or production (Oakdene Hollins 2007).

As concern about the potential of catastrophic climate change grows, there is strong public support for investment in sustainable, renewable energy alternatives to fossil fuels. But all too often industry and governments are prepared to promote new (or old) technologies with a thick veneer of 'greenwash', presenting them as environmental saviours despite evidence of serious environmental risks, costs or challenges (for example the renewed marketing of nuclear as a 'green' solution to climate change, or the oxymoron of 'clean coal'). The hype around nanotechnology fits this pattern.

Nanotechnology, the so-called 'science of the small', has been the subject of consistent and often unqualified promotion by governments and industry. Nanotechnology is being marketed as the ultimate 'techno-fix'. Some have even claimed that nanotechnology will break the tie between resource use and economic expansion, allowing us to continue business as usual growth, while reducing energy consumption and greenhouse gas emissions.

Nanotechnology proponents suggest that it will enable accelerated economic expansion, more extensive fossil fuel extraction, greater air travel and new generations of consumer goods – all at a vastly discounted environmental cost. Some of the following media headlines provide a sense of how hyperbolic this nano hype has become: "Nanotechnology and Carbon Capture Can Yield an Endless Supply of Fuel and Chemicals" (Parrish 2010); "nanotech processes can produce cheap solar panels by the acre, finally delivering on the promise of low-cost solar energy" (lightbucket 2008); "[nano will allow for] a permanent inexhaustible supply of carbon containing fuels or products" (Parrish 2010).

Nanotechnology, the so-called 'science of the small', has been the subject of consistent and often unqualified promotion by governments and industry. Nanotechnology is being marketed as the ultimate 'techno-fix'.

The results of Friends of the Earth's investigation demonstrate that these claims are misplaced. Far from offering 'silver bullet' solutions, nanotechnology may in fact impose a new level of energy and environmental costs.

what is nanotechnology and how is it used?

Nanotechnology is a powerful new technology for taking apart and reconstructing nature at the atomic and molecular level. It is being touted as the basis of the next industrial revolution and will be used to transform and construct a wide range of new materials, devices, technological systems and even living organisms.

Nanotechnology involves the design, characterisation, production and application of structures, devices and systems by controlling shape and size at the extremely small 'nanoscale'. The International Standards Organisation (ISO) defines a 'nanomaterial' as having one or more dimensions that measure less than 100 nanometres (nm), or an internal structure or surface structure at this scale (European Commission 2010).

The fundamental properties of matter change at the nanoscale. The physical and chemical properties of nanoparticles can be quite different from those of larger particles of the same substance. Altered properties can include but are not limited to colour, solubility, material strength, electrical conductivity, magnetic behaviour, mobility (within the environment and within the human body), chemical reactivity and biological activity.

The altered properties of nanoparticles have created new possibilities for profitable products and applications. Most 'first generation' nanoproducts contain passive nanoparticles that impart novel properties, for example T-shirts that contain nanoparticles of silver to impart antibacterial properties, or car body parts made from polymer composites strengthened through addition of carbon nanotubes (see Glossary).

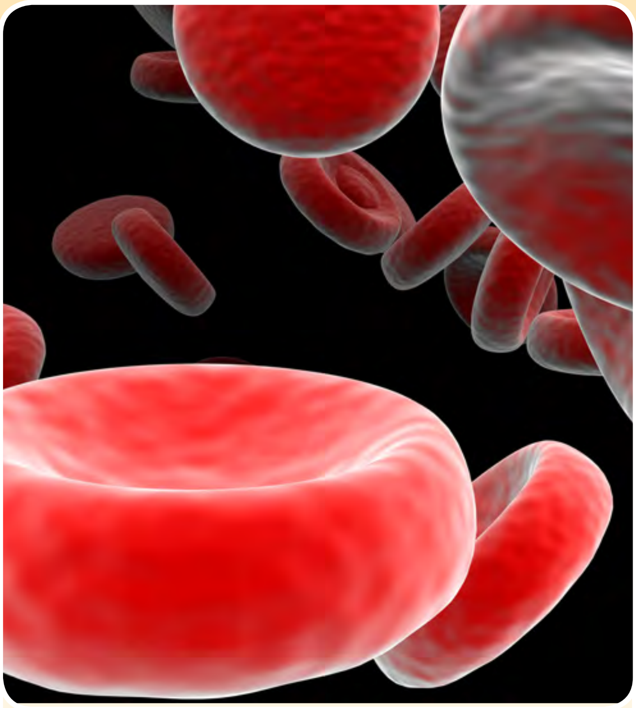
The use of nanoparticles, the potential of nanofabrication, and molecular manufacturing, have attracted keen interest from the research and business communities. In the US, the Department of Energy (DOE) has constructed five new nanoscale research centres with the mission to "support the synthesis, processing, fabrication and analysis at the nanoscale... [providing] the nation with resources unmatched anywhere else in the world" (CNMS n.d.). Much of this enthusiasm is backed by the belief that nanoscale engineering will allow for:

- More powerful, versatile and inexpensive solar panels;
- Stronger and lighter wind turbines;
- More extensive identification of oil and gas reserves and more effective extraction;
- More powerful and longer lasting batteries;
- Methods for harnessing hydrogen energy;
- Greater efficiency in lighting;

- Energy saving insulation materials;
- Lubricants able to increase the function and lifespan of machinery;
- Efficiency gains in fossil fuels through nano catalysts; and
- Stronger and lighter materials to improve transportation efficiency.

Most nanoparticles are not developed or used for energy efficiency or to reduce a product's environmental footprint.

Intentionally manufactured nanoparticles are already found in a wide range of other products, such as cosmetics, sunscreens, clothing, paints, cleaning products, sporting goods, household appliances, surface coatings, agricultural chemicals, food packaging, 'health' supplements, industrial catalysts and building equipment. Most nanoparticles are not developed or used for energy efficiency or to reduce a product's environmental footprint. The burgeoning commercial use of nanoparticles in these products will also have an impact on the energy demands and environmental costs of manufacturing. Early life analyses demonstrate that the ecological burden of nanomaterials manufacturing is far greater than that of conventional scale (larger) materials (Khanna et al. 2008; Sengul et al. 2008; see sections following).



To get some sense of scale, consider that a human hair is approximately 80,000nm wide, a red blood cell 7,000nm wide and a strand of DNA 2.5nm wide. A nanomaterial 100nm in size is approximately 800 times smaller than the width of a strand of hair, and 70 times smaller than a red blood cell. The smallest nanomaterials exist at the same scale as our bodies' DNA.

nano-based energy generation, storage, and savings

Following is a summary of the nanotechnologies most commonly promoted as solutions to the energy and climate crisis. Many of these technologies use nanomaterials or nanosystems to extend or alter the capacity of existing technologies. As with other technologies, nano applications are often combined into larger systems, for example, nanobatteries can be used alongside nano solar panels in solar energy farms, and nanocoatings, insulators, and energy storage devices can help store energy produced.

Renewable energy technologies such as solar power and wind offer important opportunities to move away from greenhouse gas-intensive fossil fuels. Nonetheless, all renewables have an environmental footprint. Our interest lies in whether nanotechnology provides solutions that improve on the functionality of existing technologies, the impact of nanotechnology use on a technology's life cycle emissions and energy demands (whether its use saves energy or requires more), and the extent to which nanotechnology imposes new environment or health burdens.

Measuring electricity

Units of electrical power are measured as watts. One thousand watts is equal to one kilowatt (kW). A megawatt (MW) is one million watts, a gigawatt (GW) is one billion watts, and a terawatt (TW) is one trillion watts.

Large-scale energy consumption and production is often measured in watt hours (Wh). The US Energy Information Administration (EIA) defines a watt hour as "an electric energy unit of measure equal to one watt of power supplied to (or taken from) an electric circuit steadily for one hour" (US EIA n.d.). Megawatt hours measure the amount of electricity produced by an electric generator over time; a megawatt measures how much electricity the generator can produce. For example, one kilowatt hour will power a 100 watt light bulb for 10 hours (Johnson 2009). Electricity generated worldwide in 2006 was 19,015 terawatt hours (TWh; Johnson 2009).

Electricity consumption

There are substantial differences in household electricity consumption internationally (Table 1). Wealthy countries use far more electricity than poorer countries, but even among the industrialised countries there is large variation. Households in the United Kingdom (UK) use less than half the electricity used by households in the United States (US).

Table 1: Electricity consumption per household differs widely between countries

Country or Region	Electricity consumption per household (kWh; year measured)	Number of people per household (year measured)	Reference
United States	11,040 kWh (2008)	2.5 (2010)	(US EIA 2010)
Australia	7,987 kWh (2007)	2.6 (2006)	(ESCAP 2010)
United Kingdom	4,800 kWh (2007)	2.36 (2001)	(UK BERR 2007)
China	1,392 kWh (2007)	2.98 (2005)	(ESCAP 2010)
India	561.6 kWh (2007)	5.4 (2001)	(ESCAP 2010)
Bangladesh	336 kWh (2007)	5.6	(ESCAP 2010)

Nano and solar energy

Summary

Use of nanotechnology in thin film solar panels enables 'roll to roll' printing and easier manufacturing. Panels based on flexible steel and plastic also allow a greater range of applications, for example on portable objects. Manufacture of some forms of thin film and nano solar panels is possible at costs that are lower than that of conventional silicon panels, although recent massive Chinese investment in silicon PV panels has reduced their costs. Further, the solar conversion efficiency of nano-based solar panels still lags considerably behind that of silicon panels: 6-13 percent compared to around 20 percent. The nano sector has been plagued with problems scaling up laboratory achievements to commercial products. The durability of dye-sensitised nano solar panels and fullerene-based organic panels is less than ten years – fifteen to twenty years less than that of conventional silicon panels. This further reduces the life cycle energy efficiency of these nanopanels. Nanomaterials used in nano solar, including silver, cadmium and other heavy metals, pose toxicity risks for human health and the environment. End of life recovery of nanomaterials and recycling is uneconomic, requiring government intervention to prevent irresponsible disposal of panels and to recover rare metals and rare earths. The scarcity of metals such as indium and gallium may be a near term constraint to the widespread development of some thin film nano solar.

Background

Electricity can be produced using photovoltaic (PV) materials in solar panels that act as semiconductors. Beyond domestic use, PV panels are also beginning to be deployed in large-scale solar power stations. PV panels work by absorbing the sun's radiation, then transferring it to supply power. Photovoltaic solar panels rely on technologies as complex as those used in computer semiconductors (otherwise known as computer chips) which are used to store memory in small devices. Most PV panels are made from thick 'wafers' of silicon. The silicon is fragile, limiting the range of settings in which panels can be used. Manufacturing PV panels from silicon is also more costly than generating the same energy via fossil fuels.

Another growing area of solar power is 'solar thermal'. Unlike photovoltaics, solar thermal uses the energy in sunlight to generate heat, rather than electricity. Low and medium temperature collectors are commonly used to heat swimming pools or the water or air in homes or businesses. High temperature collectors concentrate sunlight using mirrors or lenses, and then use this heat energy to generate electricity (concentrated solar power; NREL n.d.). Concentrated solar power can use existing energy storage technologies and conventional electric power generating plants (for example steam plants) that historically have been interfaced to the grid and distribution networks (NSTC Committee on Technology 2010). This makes it attractive to major utility companies and governments looking to use renewable energy while continuing centralised power generation.

A key attraction of solar thermal is the capacity to store energy in the form of heat. Although the costs are still high, a researcher at the US National Renewable Energy Laboratory (US NREL) suggests that solar thermal can now store up to around 16 hours' worth of energy (Beyond Zero Emissions 2009). A study by Stanford University researchers found that 93 per cent of California's annual grid electricity could be supplied by solar thermal power stations that had 15 hours storage. Solar thermal stations with storage could supply 95 per cent of the US annual grid, using land of 140 kilometres square (Manning 2009).

How is nanotechnology claimed to improve existing technology?

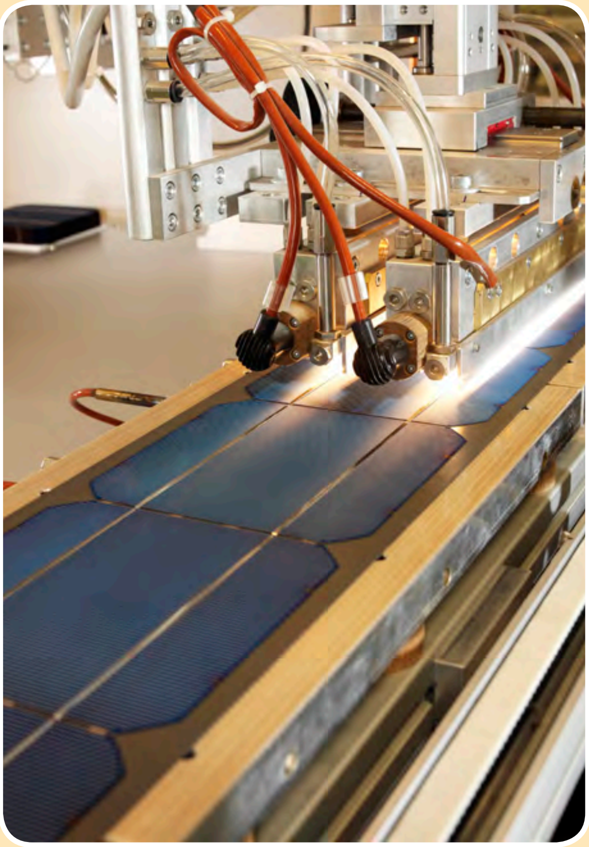
Nanotechnology is enabling the manufacture of thin film solar panels that use much less silicon. In the case of 'organic' or plastic based PV panels, no silicon is used. Nano solar proponents have asserted that by increasing solar energy conversion efficiency ('efficiency'), extending the range of places in which solar panels can be used, and reducing production costs, nanotechnology will enable solar panels to compete with fossil fuel energy.

A key breakthrough has been the development of 'roll to roll' printing (similar to newspaper printing) of nano PV components onto foil or plastic substrates. Roll to roll printing offers greater flexibility than the manufacture of silicon solar cells. It is also believed that thin film is cheaper to produce, although many companies do not disclose the cost per watt, and recent price reductions have been achieved with silicon panels (see sections following). The disadvantage is that roll to roll printing introduces a greater level of defects into panels (Gupta, et al. 2009).

Plastic and foil substrates used in some thin film don't need the bulky aluminium or glass frames of silicon solar panels. They can be incorporated onto a greater variety of building substrates, and even moving objects such as luggage or computers.

Companies that sell nano solar panels to solar power plants claim that the key benefit nanotechnology offers is the speed with which the panels can be deployed. In providing panels for a German power plant, Nanosolar claimed that a station 10MW in size could be "up and running in six to nine months compared to 10 years or more for coal-powered stations and 15 years for nuclear plants" (Vidal 2007).

There are three key areas in which nanotechnology is mooted for use in solar thermal: in coatings to improve the collection capacity of concentrated solar power receivers; for use in heat energy storage liquids to improve their thermal properties; and in the development of efficient thermo-electric (heat-electricity) converters (NSTC Committee on Technology 2010). Companies are also selling nanomaterial-based coatings to insulate solar thermal storage.



How is nanotechnology used?

Nanomaterials have an increased surface area to volume ratio. Coupled with their novel optical and electrical properties, this could allow them to capture greater quantities of the sun's light than is possible in silicon panels. There are several nanomaterials being incorporated in thin film solar cells, including fullerenes, titanium dioxide, silver, quantum dots and cadmium telluride.

Quantum dots are nanoscale spheres of inorganic materials that show novel optical properties, enabling light from different wavelengths to produce visible light. Cadmium selenide quantum dots mixed with other nanoparticles, such as titanium dioxide nanotubes (hollow cylinders) have the potential to increase solar cell efficiency by absorbing different wavelengths of light at the same time, which is not possible with other solar cell systems (Berger 2008). The Stanford PULSE Institute for Ultrafast Energy Science has researched the potential of quantum dots to improve solar cell efficiency, demonstrating that in laboratory conditions one photon of light can generate multiple electrons (Tuttle 2009).

A thin film solar cell (TFSC), also called a thin film photovoltaic cell (TFPV), is a solar cell that is made by depositing one or more thin layers (thin film) of photovoltaic material on a substrate. The thickness range of such a layer is wide and varies from a few nanometres to tens of micrometers. Many different photovoltaic materials are deposited with various deposition methods on a variety of substrates. Thin film solar cells are usually categorised according to the photovoltaic material used:

- Amorphous silicon (a-Si) and other thin film silicon (TF-Si)
- Cadmium telluride (CdTe)
- Copper indium gallium selenide (CIS or CIGS)
- Dye-sensitised solar cell (DSC) and other organic solar cells
- Thin film silicon (uses amorphous, proto-crystalline, nano-crystalline or black silicon). Thin film silicon is opposed to wafer (or bulk) silicon (mono-crystalline or poly-crystalline).

A key potential nanotechnology application for solar thermal is in the fabrication of concentrated solar power 'receivers' and the development of high solar optical absorption materials and coatings that can operate at high temperatures under high solar concentration fluxes (NSTC Committee on Technology 2010). Nanocoatings on the receivers' surface could improve their thermal capture and thermal transfer properties as well as providing corrosion resistance (Berger 2009a).

Research into using nanomaterials to improve the thermal properties of liquids for heat storage at solar thermal power plants is at an early stage. However, researchers suggest that adding nanomaterials to fluids could be one of the ways in which the capacity for heat storage is increased (Beyond Zero Emissions 2009).

Proponents also hope that nanomaterials with thermoelectric properties will increase the efficiency of converting heat to electricity (NSTC Committee on Technology 2010). The hope is that thermal energy could be harvested from waste heat created during solar power generation by thermoelectric devices. As an example, functionalised carbon nanotube films are being explored as potential thermoelectric materials that could absorb heat and provide electricity. However, again, this research is at a very early stage.

Commercial presence

Nanophotovoltaics are increasing their commercial presence, although they still make up a small fraction of the sales of silicon panels. Global sales of PV were worth approximately US$38.5 billion in 2009. Jason Eckstein, solar analyst at nanotechnology analyst firm Lux Research, estimates that crystalline silicon has 75 percent of the world market for all solar technologies. Cadmium telluride thin film panels, primarily from First Solar, have 12 percent of the market, while CIGS has only a 1 to 2 percent share (Voith 2010). One organic electrical specialist and academic has observed that most companies developing plastic solar panels remain at research and development stage: "For now, we can safely claim that organic [plastic] photovoltaics has a nearly zero percent share of the market" (Jacoby 2010). Large-scale arrays of titanium dioxide-based nanofilaments (including nanotubes and nanowires) are already being used in photovoltaic cells (Berger 2009b).

First Solar is by far the largest supplier of nano solar cells. In 2009 it was the world's largest manufacturer of PV panels, shipping more than a gigawatt of solar panels during the year (RenewableEnergyWorld.com 2010). Company Nanosolar produces thin film solar panels made from a PV nanoparticle ink composed of Copper Indium Gallium Selenide (CIGS). This nano ink is printed onto flexible metal foil through a production process similar to a printing press, and then encased in glass. Walmart recently partnered with two CIGS manufacturers, SolarCity and MiaSolé, to install thin film solar panels at 20 to 30 of Walmart's buildings in Arizona and California (Walmart 2010). Ironically, SolarCity will also be installing a large number of conventional silicon panels for Walmart, most of them made in China at low costs (Woody 2010).

Konarka, another supplier of nano solar cells, has recently opened what it claims is the world's largest roll-to-roll flexible plastic film solar manufacturing facility (Konarka 2010). In a substantial breakthrough, the company has partnered with Traveler's Choice to develop a range of travel bags and luggage that incorporate its flexible solar panels, which can in turn power small hand held devices (Konarka n.d.). Konarka claims that in full sun, a solar bag can recharge a cellular phone in two hours. The line has recently become available in retail outlets in the northern hemisphere.

It is not clear whether any solar thermal stations are using nanomaterials in their storage fluids. However, some companies are marketing nanoproducts for use in solar thermal. Nansulate sells a nanomaterial-based coating which it claims improves the insulation properties of solar thermal storage (Nanotechnology Now 2010).

> ***Amidst the hype that nano solar technologies will soon deliver energy at half the price of oil, coal or gas, in 2007 nanotechnology analyst Cientifica's CEO warned that the obstacles to scaling up laboratory discoveries were considerable and that a 'reality check' was required regarding its promise.***

Does nanotechnology deliver?

There is debate about the extent to which nanotechnology offers real breakthrough potential in solar energy. Amidst the hype that nano solar technologies will soon deliver energy at half the price of oil, coal or gas, in 2007 nanotechnology analyst Cientifica's CEO warned that the obstacles to scaling up laboratory discoveries were considerable and that a 'reality check' was required regarding its promise (Harper 2007). The challenges associated with taking a nano solar lab discovery and scaling it up to deliver a marketable product have proven prohibitive for many companies. A Lux Research analyst has cautioned that even high profile companies making thin film photovoltaics who claim to be using nanotechnology to lower costs have struggled to scale up laboratory achievements and to still achieve a functioning product (Lubick 2009). As a recent New York Times article highlights, "producing CIGS cells on a mass scale has turned out to be a formidable technological challenge" (Woody 2010).

A group of US researchers has cautioned that amongst the buzz surrounding nano solar are "questionable claims on the scientific facts" (Gupta, et al. 2009). They are pessimistic about nano solar's prospects: "nanostructure solar cells are unlikely to play a significant role in the manufacturing of future generations of PV modules" (Gupta, et al. 2009). They blame unrealistic assumptions involved in theoretical work and a failure to take into account manufacturing and scale-up constraints for the misplaced hype about nano solar's potential.

One of the key areas where nanotechnology has offered an advantage until recently is in reducing production costs. As a general rule, thin film modules (sets of panels) are lower priced than silicon modules for equivalent energy powers (Solarbuzz 2010). In its October 2010 review of the solar module retail price environment, Solarbuzz found that the lowest retail price for a multi-crystalline silicon solar module was US$1.97 per watt from a US retailer. The lowest retail price for a mono-crystalline silicon module was $2.21 per watt (€1.61 per watt), from a German retailer. The lowest thin film module price was US$1.40 per watt from a US-based retailer (Solarbuzz does make the point that technical attributes and prices are variable).

In spite of this, the cost advantage associated with using thin film nano solar has been eroded in recent months. Falling costs of silicon have lowered the costs of manufacturing silicon cells. Massive investment by the Chinese government to expand significantly its solar production has helped drive the price of solar panels down 40 percent in the past year (Woody 2010). "The solar market has changed so much it's almost enough to make you want to cry," Joseph Laia, chief executive of thin film company MiaSolé told the New York Times.

Another area where nano solar offers an advantage over silicon solar is in flexibility of production and of panel use. The minority of nano solar panels which are based on plastics rather than silicon can be transported more easily and are far less fragile. The light weight panels can be used in a greater diversity of settings, including mobile applications such as laptops or travel luggage. Konarka is now offering solar panels for use on travel luggage, to power laptop computers or mobile phones (Konarka n.d.). Thin film flexible panels installed on roofs or other building structures are very low in weight, are not subject to wind lifting, and can be walked on (with care).

Conversely, nanotechnology has not delivered in the key area of solar power efficiency. Although nano-proponents hope that in the future nanotechnology will deliver higher efficiency solar panels than silicon panels, to date the efficiency of nano solar panels is considerably less than that of traditional silicon panels (Tables 2 and 3). Despite the achievement of high efficiency in laboratory trials, manufacturers have struggled to replicate these in commercial applications. An early laboratory discovery led to suggestions that future generations of quantum dot solar panels could deliver 44 percent efficiency under normal light conditions, and up to 68 percent under sunlight concentrated by a factor of 500 (NREL 2007). But so far higher efficiency for quantum dot panels has only been demonstrated in laboratories (Kongkanand, et al. 2008). Similarly, Nanosolar achieved an NREL verified 15.3 percent efficiency in a 2009 laboratory sample of its CIGS panels, yet its commercial panels have only 8-9 percent efficiency (Cheyney 2010a; Nanosolar 2009).

Nano solar company MiaSolé received a lot of attention recently when its solar panels achieved 14.3 percent solar conversion efficiency (MiaSolé 2010). This was indeed a remarkable achievement; until now the average rate of solar conversion efficiency for nano-based cells was around 10 percent. Nonetheless, this still lags behind the twenty percent plus efficiency achieved for silicon solar cells (Tables 2 and 3). First Solar claims that its cadmium telluride thin film cells remain efficient in warm weather, on cloudy days and in situations of diffuse daylight (First Solar n.d.). Nonetheless, the efficiency of First Solar's panels is only 11.2 percent.

Table 2: Efficiencies and cost per watt of PV panels reported by a sample of nano solar companies

Type of solar cell	Company	Efficiency (of production panels unless otherwise stated)	Cost per Watt
Nano (polymer-fullerene on flexible plastic)	Konarka	6.4% in 2009 (Wemett 2009)	<US$1.00 (Condon 2008)
Nano (CIGS on foil in glass)	Nanosolar	8-9% in 2010 (Cheyney 2010a)	Sell products for US$1/ watt (Madrigal 2009)
Nano (CIGS on flexible stainless steel)	Global Solar	11% in 2010 (Cheyney 2010b)	Company declines to disclose (Wesoff 2010)
Nano (cadmium telluride on glass)	First Solar	11.2% in 2010 (Osborne 2010)	US$0.76 (Osborne 2010)
Nano (CIGS on glass)	HelioVolt	12.2% in 2008 (of a 'champion' panel, not their average; Kho 2008)	Not yet commercial
Nano (CIGS on glass)	MiaSolé	14.3% in 2010 (Solar Daily 2010)	US$0.85 (Fehrenbacher 2010)

Table 3: Confirmed PV module efficiencies measured under the global AM1.5 spectrum (1000W/m2) at a cell temperature of 25°C *(from Table II Green, et al. 2010)*

Type of solar cell	Efficiency
Silicon (crystalline)	22.9 ± 0.6%
Silicon (large crystalline)	21.4 ± 0.6%
Silicon (multi-crystalline)	17.3 ± 0.5%
Silicon (thin film poly-crystalline)	8.2 ± 0.2%
CIGS	13.8 ± 0.5%
CIGS (cadmium free)	13.5 ± 0.7%
Cadmium telluride	10.9 ± 0.5%
Amorphous silicon/ Amorphous silicon-germanium/ Amorphous silicon-germanium (tandem)	10.4 ± 0.5%

The durability of some nano solar panels is also considerably less than that of silicon panels. Nano solar has recently commissioned a report which estimated that its Copper-Indium-Gallium-(Di) selenide (CIGS) panels on flexible foil will last 25 years (Cheyney 2010b). However, dye-sensitised solar panels and fullerene-based organic panels have an active service life that is well below 10 years, compared to the 25-30 years expected from silicon cells (Reijnders 2010). Konarka's plastic panels last only 5-6 years. If the energy needed for producing these panels is taken into account, the overall life cycle energy efficiency of these solar panels is further reduced.

Bucking the 'smaller is better' trend, Gupta et al. (2009) conclude that ultra large-scale manufacturing of larger groups of silicon panels is required to lower costs of production, and predict that silicon-based PV manufacturing will continue to be the basis for future growth in the sector. The recent massive expansion of Chinese silicon solar panel production, the drop in silicon panel costs and the increase in Chinese market share of solar sales (Woody 2010) may lend support to this view.

Sustainability and life cycle issues

Proponents of thin film nano solar argue that the sector has years of growth before it has to worry about running out of raw materials (Edwards 2010). However, scarcity analysts have warned that the growth of nano solar may be imminently curtailed due to its reliance on scarce minerals such as indium and gallium, and rare earths such as selenium and telluride. The reserves of both indium and gallium are disputed. However, German researchers suggest that we have less than ten years before we run out of indium (Cohen 2007). Dutch researchers argue that because thin film nano solar based on cadmium telluride and CIGS is reliant on scare minerals such as indium and gallium, these technologies will never be able to contribute more than 2 percent of global energy demand, due to resource constraints (Kleijn and van der Voet 2010). They caution that governments should require careful resource constraints assessment before further funding of these thin film technologies: "Large scale government funding for technologies that will remain marginal is not an efficient way to tackle the energy and climate crisis" (Kleijn and van der Voet 2010, section 4.2).

What is life cycle assessment?

Life cycle assessment (LCA, also known as life cycle analysis or cradle to cradle analysis) is a technique to assess each and every impact associated with a given process or product. This includes: raw materials mining or extraction; materials processing; product manufacture; product transport and distribution; product use; repair and maintenance; and end of life disposal or recycling. The goal of LCA is to obtain a complete understanding of the environmental demands and implications of a given process or product. This is particularly important to avoid shifting problems associated with one part of a product's life cycle (for example emissions in use) to another (for example high energy and chemical demands of manufacturing).

The United Nations Environment Programme (UNEP) has warned that despite concern within the high tech sector over scarcity and high prices of minerals such as indium and gallium, only around one percent of these crucial high-tech metals are recycled, with the rest discarded and thrown away at the end of a product's life (UNEP 2010a). UNEP commissioned a report that found that unless end-of-life recycling rates are increased dramatically, specialty and rare earth metals could become "essentially unavailable" for use in high tech products.

Companies such as Walmart have claimed that because thin film nano solar cells contain fewer raw materials, their overall life cycle environmental impact is lower than that of traditional silicon solar cells (Walmart 2010). However, such claims ignore evidence that the environmental burden and energy costs of producing nanomaterials are very high (see sections following).

There are few life cycle assessments (LCA) of nano solar PV panels, making it hard to determine net life cycle energy gains or costs comparative to silicon cells. Similarly, it is difficult to establish whether the manufacturing process for nano solar is more or less toxic, and environmentally burdensome, than the manufacture of silicon solar cells.

Based on PV production data from 2004–2006, one study compared the life cycle greenhouse gas emissions, criteria pollutant emissions, and heavy metal emissions from four types of major commercial PV systems: multi-crystalline silicon, mono-crystalline silicon, ribbon silicon, and thin film cadmium telluride

(Fthenakis, Kim and Alsema 2008). It found that production of thin film cadmium telluride required the least amount of energy to produce, and so had the lowest harmful emissions based on current US and European electricity grid mixes. However, the researchers noted that differences in the emissions between different PV technologies are very small in comparison to the emissions from conventional fossil energies that PV could displace.

A recent LCA review of solar panels found that when the life span of a nano-crystalline dye sensitised solar panel is assumed to be 20 years, the grams of carbon dioxide equivalent emissions generated per kilowatt hour are roughly equivalent to those of amorphous (thin film) and poly-crystalline silicon panels, and less than those of mono-crystalline panels (Sherwani, Usmani and Varun 2010). However, when the life span was assumed to be 5 years, the emissions per kilowatt hour of the nano-crystalline cell were higher. A group of US researchers recently presented findings that organic nano solar panels had reduced life cycle energy demands compared to inorganic panels (Science Daily 2010). However, this work is yet to be published and there are few details available.

In contrast to these findings, a study in the Journal of Cleaner Production assessed the environmental demands and performance of dye-sensitised nano solar cells and fullerene-based organic cells and found that they were not more environmentally friendly than silicon solar for the following reasons:

> …high energy and materials inputs in the production of nanoparticles, a relatively low solar radiation to electricity conversion efficiency, a relatively short service life, the use of relatively scarce metals and relatively poor recyclability, if compared with the multi-crystalline Si [silicon] solar cell which currently is the market leader. Moreover, the lack of data and the inability of current methods to handle hazards of nanoparticles generate problems in conducting comparative life cycle assessment of nanoparticulate solar cells (Reijnders 2010, 307).

Reijnders (2010) observes that "in actual development work [of nano solar] there seems to be no focus on achieving (net) environmental improvement. This is at variance with the attention to environmental improvement in the development of other types of solar cells." This is in direct contrast to the claims made by nano solar companies who promise to create green solutions for energy generation.

Concerns about the end of life toxicity risks of nano components used in its solar cells, in particular cadmium, has prompted First Solar, Inc. to commit to an end-of-life collection scheme for its panels. This is a commendable initiative, although it is not the industry norm. Further, researchers warn that because the economics of recycling solar PV panels are unfavourable, voluntary initiatives are not enough (McDonald and Pearce 2010). They caution that voluntary initiatives will face future economic stress and that unless recycling is mandated, hazardous materials will inevitably enter local waste streams.

Given the very early stage of this research, no life cycle analyses are available for the use of nanomaterials in solar thermal applications.

Health and environment risks

Many nanomaterials used in the nano solar sector incorporate heavy metals and pose inherent toxicity. First Solar, which dominates the thin film PV market, uses cadmium telluride. Other applications in development use quantum dots that have cadmium cores. Early studies suggest that quantum dots could be transferred along food chains, could bioaccumulate or even biomagnify, and that in time coatings could degrade, exposing their toxic cores (see health and environment section following).

The health risks associated with carbon nanotubes, in particular their potential to cause mesothelioma and disease similar to that caused by asbestos, have also attracted international concern (see health and environment section following). These risks are likely to be most acute for workers exposed during manufacturing. Titanium dioxide nanotubes have a similar shape to carbon nanotubes. A test tube study on lung epithelial cells found that they

The German sustainability research group Wuppertal Institute suggest that even if recycling schemes are mandated, persistent concerns about the health harm associated with cadmium mean that it should not be used in solar panels at all (Saurat and Ritthof 2010).

had a strong dose-dependent effect on cell proliferation and cell death (Magrez, et al. 2009).

Early studies also show that nano forms of titanium dioxide, silver and carbon fullerenes, all touted for use in nano solar, can be toxic to people and the environment (see health and environment section following).

The Silicon Valley Toxics Coalition provides an excellent detailed report on other toxic aspects of the solar energy industry (Silicon Valley Toxics Coalition 2009).

Nano and wind energy

Summary

The energy demands of manufacturing carbon nanofibers and nanotubes used to reinforce windmill blades are high compared to existing materials. Early life cycle analysis shows that although using nanocomposites will reduce the weight of windmill blades and may extend their service life, it may or may not reduce life cycle energy demands; use of nanotechnology could increase energy demands. In situations where the durability of wind turbines may be greatly diminished (for example at sea or in icy conditions) nanocoatings may extend windmill blades' service life. There is no life cycle analysis yet of the energy implications of the use of nanocoatings. There are serious health concerns regarding carbon nanotubes, mooted for use in nanocomposites for windmill blades and for coatings. Studies have shown that some forms of carbon nanotubes can cause mesothelioma, the deadly disease associated with asbestos exposure.

Background

Electricity is produced from wind via the rotation of usually fibreglass or aluminium blades, somewhat similar to airplane propellers, which set in motion turbines that generate electricity (usually grouped into wind farms). According to the Global Wind Energy Council, global wind energy capacity was more than 120 GW in 2008 (Pullen, Liming and Sawyer 2008), supplying over 1.5 percent of the world's electricity (World Wind Energy Association 2009).

Wind energy is valued as one of the most environmentally benign methods for producing energy. It has the potential to supply 10-12 percent of global electricity demand by 2020. As of 2008, wind energy was already saving 158 million tons of CO^2 every year – the equivalent to taking over 27 million US cars, or nearly 40 million Australian cars, off the road (Pullen, Liming and Sawyer 2008).

How is nanotechnology claimed to improve existing technology?

Researchers are attempting to use nanotechnology to create stronger, lighter and more durable windmill parts. Nanocoatings are being developed to protect windmill blades and to extend their service life. The use of nanoscale lubricants is also being investigated to reduce friction and to extend the service life of parts. Researchers have begun investigating nanoparticles for use in sensor technologies to alert to damage in wind turbines.

How is nanotechnology used?

Carbon nanotubes – cylinders made of carbon atoms that are 10,000 times thinner than a strand of human hair – are one of the nanomaterials that have been the subject of much hype. They are the stiffest and strongest fibres known and also have unique electrical properties. Finnish company Eagle Windpower Oy has used carbon nanotubes bound with epoxy in its small windmill blades (Understanding Nano.com 2009). The company claims that as a result, the blades are approximately 50 percent lighter than competing glass fibre blades and can start operating at low wind speeds of 2-2.5 meters per second. The company says that use of the nanotubes enables the station's wing size to be doubled, which results in 30 percent greater power production.

Increasing the blade size of windmills increases the amount of electricity that can be generated. Larger wind turbines can measure up to 60 meters in length. However, the limits of glass fibre-reinforced plastics have been reached in this field and there is now a materials development problem in achieving larger, more resilient wind energy systems. A hybrid material is under development, which uses vapour-grown carbon nanofibers to reinforce the interface of a glass fibre/epoxy matrix (Merugula, Khanna and Bakshi 2010). This could make windmill blades stronger and lighter, although the material still faces mechanical challenges.

The UK is launching a £100 billion (approximately US$156 billion) off-shore wind project using large turbines. The project is expected to produce about a third of the country's energy by 2020 (Babbage 2010). These turbines will be installed further off-shore than any existing wind farm, where engineers will have room to build massive wind turbines not suitable for use on land (Babbage 2010). However, off-shore wind turbines can easily be damaged by harsh weather conditions at sea (Hayman, Wedel-Heinen and Brondsted 2008).

Companies are attempting to use nanotechnology to create water repellent coatings that could prevent ice and moisture build up on wind turbines, enabling higher energy production (General Electric 2009). Nanotechnology-based coatings also have the potential to extend the service life of windmill blades used in harsh weather conditions, for example at sea.

Nanoscale lubricants are also being developed that act as tiny ball bearings; researchers hope that they will diminish friction and wear and tear in turbines, making them more efficient and longer lasting.

Commercial presence

The use of nanomaterials in commercial windmill applications does not appear to be widespread, although without mandatory labelling of nanomaterials used in composites, coatings and lubricants, it is difficult to know.

Eagle Windpower Oy, is using carbon nanotubes to strengthen and lighten its small windmill blades. It produces windmills small enough to be used for a single house (2-500kW). The company claims to be participating in several projects in developing countries, and to be in negotiations with a Finnish energy company to provide electricity for its service stations (Understanding Nano.com 2009).

Baytubes® (carbon nanotubes) made by Bayer AG are currently marketed for use to fortify wind turbines and allow for larger rotor blades (Bayer AG 2009). Bayer claims that "the lightweight design of the nanotubes – and thus of the hybrid materials in which they are incorporated – boosts the efficiency of the wind-to-power conversion process" (Bayer AG 2009).

Does nanotechnology deliver?

A recent life cycle analysis of carbon nanofiber-reinforced windmill blades found that because of the huge energy costs associated with manufacturing the nanofibers, even though using the nanofiber composites may reduce the weight and increase the strength of windmill blades, it may

not deliver any energy savings over the life cycle of the blades (Merugula, Khanna and Bakshi 2010). Further, the researchers observed that there may be mechanical challenges to using the nanofibers: "weight savings by CNFs [carbon nanofibers] may implicitly assume a prohibitively thin [windmill] blade" (Merugula, Khanna and Bakshi 2010).

Effective nanosensors have yet to be developed. It is hoped that nanosensors could reveal very small cracks in wind turbines and other potential defaults in construction. The US National Renewable Energy Laboratory (NREL), part of the US Department of Energy (DOE), has tested various forms of carbon nanotubes including 'buckypaper' to create 'neurons,' which can theoretically detect strain and fractures in various materials used to build wind turbines. However, the NREL observes that there are considerable practical barriers to this application's successful use: the buckypaper was found to be "brittle and difficult to apply on large structures" (Schulz and Sundaresan 2006).

It is possible that nanolubricants will be useful in reducing friction and protecting windmill gears. However, there are several high performance non-nano oils that are well regarded for this purpose (Siebert and Holm 2009).

Sustainability and life cycle issues

It is unclear whether there are any energy savings associated with using nanomaterials such as carbon nanotubes or carbon nanofibers (CNF) to strengthen windmill blades. An early LCA study found that cradle to gate processing of CNF-windmill blades is 1.4 to 7.7 times more energy intensive than conventional material (Merugula, Khanna and Bakshi 2010). The researchers found that energy savings were dependent on variables including the manufacturing process, solvent handling and quantity of carbon nanofibers used. If CNF blades do result in both weight savings and increased life span, potential energy savings across the life cycle vary from insignificant to substantial. However, there may be practical constraints to using CNF hybrid materials; the authors conclude that "it is not yet substantiated whether replacement of long carbon fibres is advantageous both mechanically and energetically".

Further life cycle analysis is required to establish whether or not the performance and efficiency gains associated with lighter, stronger nanomaterial-reinforced blades are enough to compensate for the significant energy demands of their manufacture.

Health and environment risks

The health risks associated with carbon nanotubes, in particular their potential to cause mesothelioma and disease similar to that caused by asbestos, have also attracted international concern (see health and environment section following).

Nano and hydrogen energy

Summary

Dreams of a hydrogen-powered future, where the only emissions from cars are heat and water, have proven seductive to environmentalists, technophiles and politicians alike. Despite this, the reality is that today's hydrogen cars are powered by fossil fuels and release several times the greenhouse gas emissions of their petrol-powered counterparts. The putative hydrogen economy faces several key technical, sustainability and safety obstacles. Proponents hope that nanotechnology could help to boost the efficiency and bring down costs of renewable energy to generate hydrogen, provide new means to store hydrogen, increase the capacity and effectiveness, and reduce the costs of hydrogen fuel cells. However, developments in this field are at a very early stage. It is improbable that cars powered by renewable energy generated hydrogen will be widespread in the near future. Hydrogen-powered cars are therefore highly unlikely to make a significant contribution to cutting greenhouse gas emissions in the next ten or twenty years – the period in which such cuts are critical. In the meantime, development of hydrogen cars entrenches reliance on fossil fuels to produce the hydrogen. Further, the huge investment required to conduct research in this field and to support establishment of hydrogen power infrastructure may present a dangerous opportunity cost to the important measures we could be taking to improve mass transport options and to reduce reliance on private vehicles.

Replacing the UK's vehicle fuels with electrolysis hydrogen would take more than the country's present electricity consumption (Fauset 2008). It appears highly unlikely that in the near term nanotechnology will enable sufficient efficiency increases in renewable energy, and sufficient drops in its costs, to enable a doubling of existing electricity consumption made possible solely by renewables.

Background

The 'hydrogen economy' is a hypothetical future economy in which hydrogen is the primary form of stored energy for vehicles and industrial applications (Elcock 2007). In 2007 the then US President announced US$1.7 billion in public funding for a five year project to develop hydrogen-powered fuel cells, hydrogen infrastructure and advanced automotive technologies (Berger 2007a). At that time George W. Bush said that it would be practical and cost-effective for large numbers of Americans to choose to use clean, hydrogen fuel cell vehicles by 2020. The US Department of Energy's (US DOE) Hydrogen Program predicts that sufficient hydrogen 'technology readiness' will be achieved by 2015 to allow industry to make decisions on commercialisation (US DOE n.d.). However, despite the highly optimistic and probably unachievable predictions of George W. Bush and the Department of Energy, achieving a future hydrogen economy faces several key technical, infrastructural, economic and safety constraints.

One of the most critical issues surrounding hydrogen's use is the reliance on fossil fuels to generate it. Hydrogen is a carrier of energy not a source in its own right. A primary energy source – coal, gas or electricity – is required to produce it. Hydrogen can be produced by using fossil fuels as a 'feedstock' (hydrogen source). This requires the separation of hydrogen from carbon components of the fossil fuels. Hydrogen can also be produced by using water as the feedstock. This requires electricity to separate the hydrogen and oxygen. The scale of the electricity demands associated with substituting cars powered by hydrogen generated only by electricity for petrol cars would be enormous (see below). The US "Hydrogen Posture Plan" makes clear that it envisages ongoing reliance on fossil fuels to generate hydrogen (US DOE, US DOT 2006).

Another barrier to the widespread adoption of hydrogen as a fuel source is the very low efficiency and high costs of fuel cells that convert hydrogen and oxygen into electricity, heat and water. The technical challenges associated with developing fuel cells are considerable. Fuel cells for hydrogen cars have been plagued by consistent over-promising and under-delivery by industry. In 2004 IBM predicted that fuel cells in cars would be a "daily fact of life" by 2010, and General Motors estimated that it would have a million fuel-cell cars in production by now (Elcock 2007). Neither prediction has been realised.

Beyond the need to avoid fossil fuel use in generating hydrogen is the key challenge of how to store it. Roughly speaking, about 1 kg of hydrogen is needed to drive 100 km. That requires 50,000 litres (~14,000 gallons) of hydrogen to be stored in a vehicle tank for a car to have a 500km range (Berger 2007a). There are three ways of doing this: as a high-pressure compressed gas; a cryogenic liquid; or as a solid. To be liquefied, hydrogen needs to be cooled to -253°C. The energy used to do this is equivalent to 30-40 percent of the energy the hydrogen contains (Fauset 2008). Compressed gas requires less energy but is far less efficient. Both compressed and liquefied hydrogen pose the threat of explosion of undetected leakage (see below).

The lack of safe storage capacity, the risk of explosion associated with transporting and storing hydrogen under high pressure, and the significant, possibly prohibitive expenses associated with hydrogen infrastructure are all barriers to hydrogen's use as a fuel (Berger 2007a; Fauset 2008). The cost of infrastructure to supply just 40 percent of US light-duty vehicles with hydrogen has been estimated to cost over US$500 billion (Fauset 2008).

How is nanotechnology claimed to improve existing technology?

Most interest in nanotechnology applications in the hydrogen sector is based on early stage or laboratory scale research. A report by the United Nations University suggested that in the future nanotechnology could help to make a hydrogen economy possible through applications in the following areas: hydrogen as an energy source; hydrogen generation via electrolysis; hydrogen generation from photolysis; hydrogen fuel cells for use in transport (for example cars and buses); hydrogen storage; light metal hydrides; carbon nanotubes storage; molecular sponges (Esteban, et al. 2008).

The key areas of research are to use nanotechnology to improve the viability of hydrogen generation from renewable sources, to increase the capacity and practicality of hydrogen storage, and to increase the efficiency and lower the costs of fuel cells (Berger 2007a). There is much interest in using nano solar to help reduce costs and increase efficiencies of producing hydrogen from renewable sources (Berger 2007a; US DOE, US DOT 2006; NREL 2009). The US Department of Energy suggests that nanotechnology is essential to increase the viability of renewable energy to play any role in generating the electricity to produce hydrogen from water (US DOE, US DOT 2006).

Researchers are also investigating the potential for nanomaterials to be used for hydrogen storage and for nanobatteries to support renewable energy systems or to act as supplementary power sources in hydrogen cars (Esteban, et al. 2008; Nanowerk 2007). The most significant role for nanotechnology may be in the development of hydrogen fuel cells, electrochemical devices that convert a fuel such as hydrogen or methanol directly into electricity (Esteban, et al. 2008).

How is nanotechnology used?

The application of nanotechnology to solar energy is discussed in preceding sections. Developments in nanobatteries, including lithium ion batteries, are discussed in following sections.

One of the areas where researchers hope that nanotechnology could deliver a technical breakthrough is in photovoltaic cells that produce electricity to produce hydrogen from water. Experiments with nanowire arrays and other nanostructured materials have shown that they improve the efficiency of these cells (Berger 2007a).

Swiss company Hydrogen Solar has developed a Tandem Cell™ which it hopes will eventually generate hydrogen to power vehicles, refineries, industrial and domestic equipment (Hydrogen Solar n.d.). The Tandem Cell™ is designed to use the sun's energy to directly power electrolysis to generate hydrogen. The front cell absorbs the high energy ultraviolet and blue light in sunlight, using nano-crystalline metal oxide thin films to generate electron-hole pairs. The longer wavelength light in the green to red region passes through the front cell and is absorbed in a Graetzel Cell producing electrical potential under nearly all light conditions. Together, the cells provide the potential required to split the water molecules in the electrolyte. The cell currently has very low efficiency (3 percent); the company acknowledges that "we also need to optimise all other aspects, including the counter-electrodes, the electrolytes and the mechanical design" (Hydrogen Solar n.d.)

Researchers are also trying to develop nanomaterials that can store large quantities of hydrogen in a small space, while minimising the risk of explosion. Nanomaterials of interest include metal hydrides and chemical hydrides such as ammonia borane to which hydrogen can be bound chemically (Davis, et al. 2009). Hydrogen can also be physically bound to carbon nanotubes or metal nanoclusters (Elcock 2007), or attached to carbon nanotubes via reversible hydrogen bonds (Nikitin, et al. 2008). The stored hydrogen can then be released by heat, electricity, or chemical reaction. Based on computational modelling, some researchers have predicted that using carbon nanotubes to store hydrogen may someday enable a car or bus to be powered by a brief case sized hydrogen battery (The X-Journals 2009).

Researchers are also investigating the potential for nanomaterials to increase the efficiency and lower the costs of fuel cells that use hydrogen and oxygen to produce electricity (Cientifica 2007a). Building fuel cells can be costly, especially the platinum electrode material used inside the devices (Berger 2007a). By using nanoparticles of platinum, reactivity is increased. The reactivity of nanoparticles of platinum is greater than the reactivity of larger particles of platinum; more reactive atoms are exposed as the size of particles decreases and their relative surface area increases. By increasing the reactivity of platinum, researchers hope that less platinum could be used. This could reduce the costs of production. Researchers are also investigating whether or not it is possible to use nanoscale non-precious metal catalysts in place of the platinum (Berger 2006).

Commercial presence

It doesn't appear that hydrogen energy is currently produced, stored or converted with the aid of nanomaterials outside of a laboratory, although once again, it is very difficult to verify this. Honda has two hundred models of its FCX Clarity hydrogen car available for lease (American Honda Motor Co., Inc. 2010). This car contains lithium ion batteries which incorporate some nano components. These are used to provide an alternative power source to the hydrogen (Esteban, et al. 2008).

Hydrogen fuel cell vehicles themselves are not presently widespread on the market. Issues with creating hydrogen fuel station infrastructures, cost, and safety are persistent and significant. However, limited numbers of some makes are available, including by BMW's H7. VW, Nissan, and Hyundai/Kia also have fuel cell vehicle prototypes on the road.

Does nanotechnology deliver?

The only way for hydrogen-powered cars to be free of greenhouse gas emissions is if hydrogen is produced by electrolysis of water, powered by only renewable electricity, and if the subsequent energy-intensive liquefaction process is also powered by only renewable energy. However, Corporate Watch cautions that producing hydrogen by using electricity requires far more energy than producing it from coal or gas.

News service Nanowerk's Berger observes that the "holy grail" of nanotechnology research "would be a highly efficient device that you fill with water, put in the sun, and get hydrogen without using any outside source of energy" (Berger 2007a). However, the technical obstacles faced by manufacturers trying to commercialise thin film nano solar panels for roofs suggest that such an application may be unachievable in any foreseeable time frame.

The development of panels that use the sun's energy directly to power hydrogen production from water would be a huge step forward. However, this research is at a very early stage, efficiencies obtained so far are very low (3 percent) and its developers acknowledge the need for much more technical work and improvement.

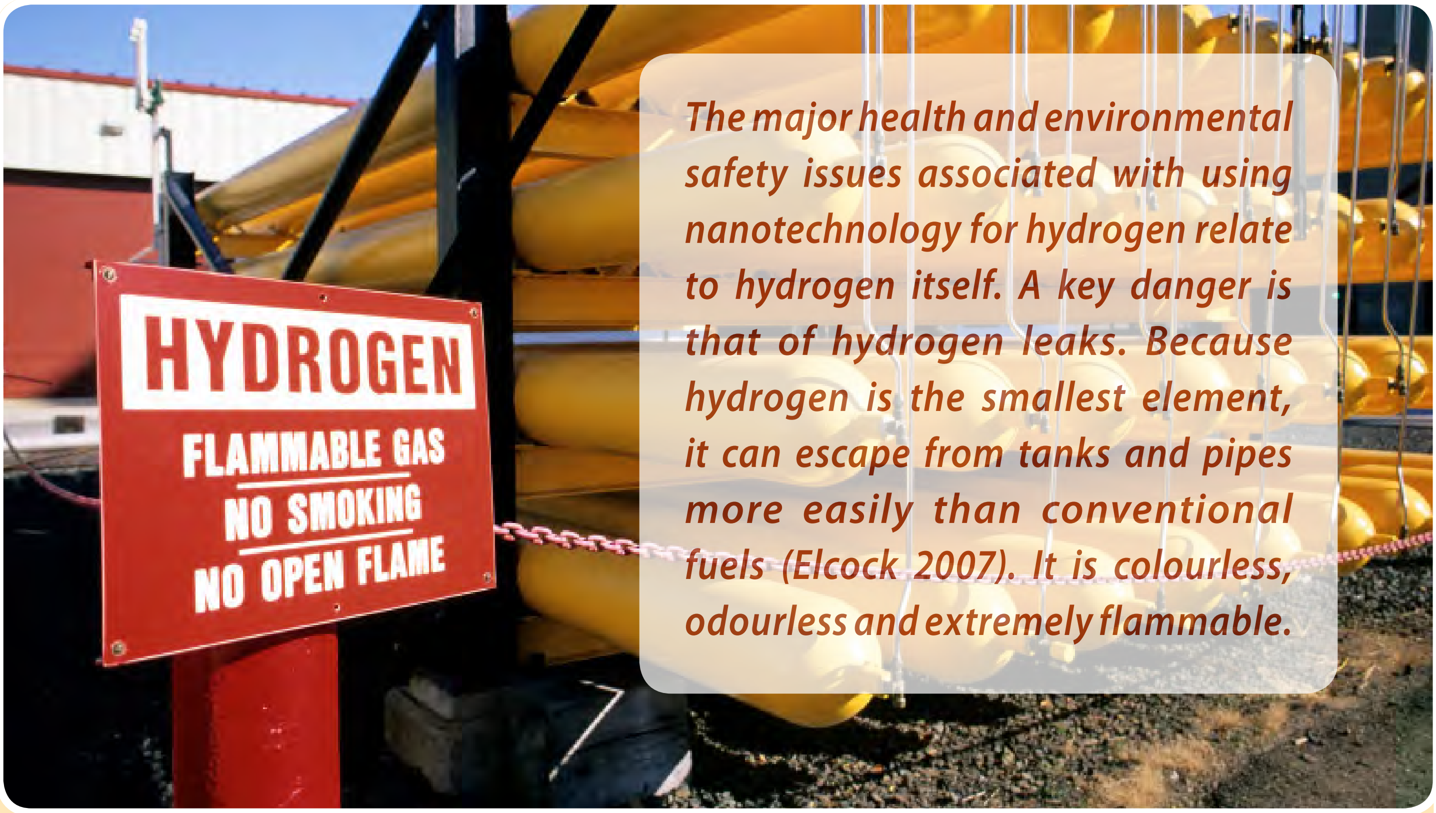
It also appears unlikely that nanotechnology will be able to solve the serious safety problems that have plagued prototypes of hydrogen cars and which make the storage, distribution and use of hydrogen fuel a serious public risk (see below).

Sustainability and life cycle issues

Researchers hope that nanotechnology could help reduce the quantity of platinum required by fuel cells. Even so, the scarcity of platinum is a constraint to widespread adoption of fuel cells. It has been estimated that if 500 million vehicles were re-equipped with fuel cells, losses (dissipation) of platinum (via exhaust fumes) would mean that all the world's sources of platinum would be exhausted within 15 years (Cohen 2007).

The most serious sustainability and life cycle issues of these applications relate to how hydrogen is produced, rather than the nanomaterials themselves. Even if nanomaterials enable improvements in hydrogen storage and fuel cell function, if hydrogen continues to be produced using fossil fuels, this will merely exacerbate the greenhouse gas emissions associated with private vehicle use.

The vast majority of the hydrogen currently produced in the US comes from natural gas (methane; NREL 2009). The problem with using methane to create hydrogen is that when the carbon is separated from the hydrogen it is released into the atmosphere as carbon dioxide. The IPCC states that even in a large modern plant, manufacturing hydrogen from natural gas emits 9.1 kg carbon dioxide per kilogram of hydrogen (IPCC 2005). Further, natural gas is not a renewable source of energy (Oil and Gas Accountability Project n.d.).



The major health and environmental safety issues associated with using nanotechnology for hydrogen relate to hydrogen itself. A key danger is that of hydrogen leaks. Because hydrogen is the smallest element, it can escape from tanks and pipes more easily than conventional fuels (Elcock 2007). It is colourless, odourless and extremely flammable.

Corporate Watch warns that producing hydrogen from electricity and compressing or liquefying it to use as a vehicle fuel – the main hydrogen application being considered - could have a worse impact on the climate than using petrol if it is not based on renewable energy (Fauset 2008). For example powering BMW's hydrogen car with hydrogen produced from water using electricity from the UK grid would create around four times the emissions of the car's petrol equivalent. Powering the same car with hydrogen produced from natural gas (methane) would still create around two and a half times the emissions of the BMW's petrol equivalent, and around six times the emissions of a Toyota Prius (Fauset 2008).

Swiss energy analysts caution that the generation of hydrogen by electricity on-site at hydrogen filling stations would require a 3 to 5 fold increase of electric power generating capacity. The energy output of a 1 GW nuclear power plant would be needed to serve twenty to thirty hydrogen filling stations on frequented European highways (Bossel and Eliasson 2003).

Berger observes that "While politicians and the energy industry talk about the clean future of the hydrogen economy, the [US] DOE's Hydrogen Energy Roadmap foresees up to 90 percent of hydrogen production coming from fossil fuels – coal, gas, oil – the rest mostly from nuclear power plants" (Berger 2007a).

Health and environmental safety

The major health and environmental safety issues associated with using nanotechnology for hydrogen relate to hydrogen itself. A key danger is that of hydrogen leaks. Because hydrogen is the smallest element, it can escape from tanks and pipes more easily than conventional fuels (Elcock 2007). It is colourless, odourless and extremely flammable. Hydrogen also burns invisibly, raising the danger not only of undetected leaks but also of undetected fires. Corporate Watch cautions that a raging hydrogen fire could be undetectable until you stepped into it and went up in flames (Fauset 2008).

Hydrogen is flammable over a wide range of concentrations and its ignition energy is twenty times smaller than natural gas or petrol (Fauset 2008). A report commissioned by the US Department of Energy warned that operation of electronic devices such as mobile phones can cause ignition and 'common static' (generated by sliding over a car seat) is about ten times what is needed to ignite hydrogen (Arthur D. Little, Inc. 2002).

Toyota had to recall its hydrogen car prototypes in 2003 due to leaking issues detected by drivers (Fauset 2008). Cars such as Honda's FCX have been fitted with sophisticated hydrogen leakage sensors (Esteban, et al. 2008). Despite this, the possibility of undetected leaks at hydrogen refuelling stations is troubling; there are no ready and reliable detection methods suitable for wide scale deployment. Until 2005, NASA's safety guidelines for hydrogen handling recommended detecting leaks in its hydrogen tanks by getting someone to walk round pushing a broom in front of them to see if the bristles caught fire (paragraph 601b(4); NASA, Office of Safety and Mission Assurance 1997).

Energy analysts have also warned that although pipe delivery of hydrogen could be energy inefficient and result in substantial leakage, road-delivery of hydrogen fuel would pose serious safety problems. Because compressed hydrogen carries so little energy value, fifteen times the number of tankers would be needed compared to supplying petrol. Swiss analysts predict that one out of seven accidents involving trucks would involve a hydrogen truck; every seventh truck-truck collision would occur between two hydrogen carriers (Bossel and Eliasson 2003).

The use of nanomaterials such as carbon nanotubes in hydrogen fuel cells also poses health and environmental risks. The health risks associated with carbon nanotubes, in particular their potential to cause mesothelioma and disease similar to that caused by asbestos, have attracted international concern (see health and environment section following).

Nanotechnologies to expand oil and gas extraction

> *"All the easy oil and gas in the world has pretty much been found. Now comes the harder work in finding and producing oil from more challenging environments and work areas."*
>
> - William J. Cummings, Exxon-Mobil company spokesman, December 2005 (Donnelly 2005)

> *"Nanotechnology offers tremendous potential for the oil and gas industries and is our best hope for extending the lifeline of our current energy resources. Nanotechnology provides numerous solutions for mapping new reservoirs, for retrieving more oil from current wells, and for making our fuel usage cleaner and more environmentally friendly."*
>
> - Nano Petroleum, Gas and Petrochemicals Industries Conference 2009 (SabryCorp n.d. a)

Summary

The world's biggest petrochemical companies are collaborating to fund research and development to use nanotechnology to double the oil and gas that can be extracted from known reserves, and to find new reserves. Similar research is being publicly funded in Australia, Mexico, the US, the UK, Japan, Saudi Arabia and other countries. The use of nanotechnology to identify new oil and gas reserves, to double extraction from existing reservoirs, and to make viable extraction from currently marginal reserves will inevitably result in the massive release of additional greenhouse gases. The environmental cost will be exacerbated by the enormous quantities of nanomaterials predicted to be used in 'enhanced oil recovery' (EOR). Nanotechnology may also result in the opening up of new drilling sites in currently unviable areas. Areas such as the Arctic, the Amazon, the Congo and elsewhere which have high ecological value and are home to indigenous peoples, have to some extent been protected by the marginal economic value of oil reserves. These areas may become more vulnerable to drilling expansion if nanotechnology increases oil recovery and reduces extraction costs.

Background

Industry observers have warned that we are approaching the maximum rate of petroleum extraction, after which we face a permanent and growing gap between supply and demand – what is called peak oil. Earlier this year the UK Industry Taskforce on Peak Oil and Energy Security warned that the UK may be rocked by oil shortages, supply and price volatility as early as 2015 (Industry Taskforce on Peak Oil and Energy Security 2010).

Many environmentalists – and even some members of the UK taskforce - have heralded the approach of peak oil with calls for a shift to less energy-intensive economic production and consumption, and to more rapid development and deployment of renewable energy. However, some governments, for example in Mexico and Saudi Arabia, have stated publicly that use of nanotechnology to extract more oil and gas is one of their top strategic research priorities (IEA 2009; Kingdom of Saudi Arabia 2007). Investing in new EOR technologies is also one of the top strategic priorities for the US Department of Energy (US DOE n.d. a.) which includes nanotechnology research (Karoub 2004). Nanotechnology research to increase oil and gas reserve discovery and oilfield extraction is also publicly funded in the UK (UK EPSRC n.d.), in Australia through the Commonwealth Scientific and Industrial Research Organisation (CSIRO; CSIRO n.d. a; CSIRO n.d. b) and in Japan (Endo, et al. 2008).

How is nanotechnology claimed to improve existing technology?

The petroleum industry and government investors hope that nanotechnology based sensors, coatings, membranes and devices will help find new oil and gas reserves, expand extraction capacity at existing wells, lower extraction and handling costs, and achieve efficiency gains.

The Nano Petroleum, Gas and Petrochemicals Industries Conference in November 2009, held in Cairo, Egypt, outlined the anticipation of nanotechnology's application in exploration, drilling, production, engineering, well logging, refining, processing and transport of fossil fuels. The conference website openly acknowledged the extent to which the fossil fuel sector is counting on nanotechnology to prolong its existence (SabryCorp n.d. a)

How is nanotechnology used?

Proponents hope that nano and microscale sensors can be developed that can be injected into oil and gas well bores. These sensors will migrate through the fractures and pores in the reservoir rock and collect real time data regarding the physical, chemical and spatial characteristics of the well space and the oil and gas within.

The CSIRO, in conjunction with two Australian universities, is developing nano chemical sensors to enhance discovery rates of untapped oil or gas deposits beneath the seabed (CSIRO n.d. b). The CSIRO has developed highly sensitive hydrocarbon sensors that incorporate printed gold nanoparticle film attached to electrodes. These sensors can effectively detect tiny seepages of hydrocarbons released from the seabed, and can provide real time molecular information indicating fluid type. The sensors could be run continuously during marine surveys to obtain profiles of hydrocarbons in water that can be mapped in a similar way to seismic, electromagnetic and magnetic data.

In the UK, the Engineering and Physical Sciences Research Council is funding research by BP and the University of Surrey to develop 'smart injectable nanoparticles' that can be administered to reservoirs. The nanoparticles are being designed to better identify and map unrecovered oil, increasing rates of oil extraction (Gill 2009; UK EPSRC n.d.).

Temporary moratoriums on deep-sea oil drilling followed the tragic oil rig explosion in the Gulf of Mexico on April 22 this year. Difficulties associated with stemming the flood of oil at deep sea levels resulted in the worst environmental disaster in US history. Nonetheless Mexican and Japanese public funding has supported development of carbon nanotube rubber composites for use in

oil drilling at even greater depths (Endo, et al. 2008). The composites can be used in sealing materials and O-rings that can withstand extreme heat and pressure. The aim is to enable drilling in even harsher temperatures and pressure, allowing companies to extract oil that was previously unreachable because of its depth.

Nanomembranes are also being developed to better filter impurities from oil and gas. Other applications of nanotechnology in the petroleum sector include: nanocoatings to reduce corrosion of drilling components; nanocomposites to reduce the weight and increase the strength of drilling components, also enabling deeper drilling; nanocomposites to increase the strength and reduce the weight of pipes; nanolubricants to reduce friction in drilling equipment; and nanocoatings to provide improved barriers to extreme weather events (Kingdom of Saudi Arabia 2007; SabryCorp n.d. b).

Does nanotechnology deliver?

It is not yet clear to what extent nanotechnology will succeed in finding new oil and gas reserves, or increasing the viability of currently marginal oilfields.

Commercial presence

It is not clear whether or not any nanotechnology-based products are already in commercial use by the petrochemical sector; it appears that nanotechnology developments remain largely at research and development stage. However, research activity in the area is substantial.

The petrochemical industry's interest in nanotechnology is so great that 10 of the world's biggest companies have joined forces to develop new nano-based methods for oil and gas field detection and mapping (Table 4). Together with the University of Texas and Rice University, the petrochemical giants have established the Advanced Energy Consortium (AEC; Advanced Energy Consortium n.d.).

Table 4: Big oil members of the Advanced Energy Consortium, dedicated to developing nanotechnology to expand oil and gas extraction

BP America	Marathon
Conoco Phillips	Petrobras
Baker Hughes	Schlumberger
Halliburton	Total
Oxy [Occidental Petroleum Corporation]	Shell

The way in which manufactured nanoparticles move and transform in soil and aqueous and marine environments remains poorly understood, and nano-ecotoxicology attracts minimal funding. In contrast, the AEC has attracted "a world class team of interdisciplinary researchers" within a US$30 million consortium to track and map the movement of injected nanoparticles, nanocapsules and nanobots in oil and gas reservoirs (Advanced Energy Consortium 2008; Chapman and Thomas 2010). The AEC has commissioned research projects at top universities internationally. Petroleum giant Shell was so keen to promote academic-industry collaboration on nanotechnology research that it sponsored a dedicated forum in 2008 for 30 of the world's top experts in nanotechnology and 30 Shell professionals to explore how nanotechnology could be used in detection, extraction and production of oil and gas (Parker 2008).

Sustainability and life cycle issues

The most serious environmental implication of the petroleum industry's quest to use nanotechnology to expand extraction and production of oil, petrol and gas is clear: more fossil fuels extracted and burnt will result in more greenhouse gas emissions. The industry is interested in developing more efficient fuel processing and use. However, there is no expectation that increased efficiency will result in environmental savings commensurate with the extra oil reserves nano extraction is predicted to unleash. If the AEC is correct its nano applications will double the oil

Petrochemical companies suggest that nanotechnology will enable far greater rates of extraction from existing reserves, perhaps doubling the amount of oil that can be accessed by "reducing the 50 to 70 percent of today's discovered resources that remain in place, and extending the useful life of hydrocarbons to support the world's energy needs" (Chapman and Thomas 2010).

available for extraction from existing reserves.

A further environmental cost of using nanotechnology to extract fossil fuels is the energy costs of nanomaterials manufacturing and the toxicity of nanomaterials intentionally released into the environment. This would be many orders of magnitude greater than the environmental costs associated with other nanoproducts because of the huge quantity of nanomaterials involved. Usually nanomaterials are used in small quantities. However, Sergio Kapusta, Shell's Chief Materials Scientist, told E&P Magazine cautions that unlike other nano applications, using nanomaterials to track, map and help recover oil would require huge quantities: "To inject nanomaterials in a water flush [sent through a reservoir], you're talking tons, not milligrams, of material" (Parker 2008). Manufacturing tons of nanomaterials would come at a huge energy and environmental cost. Further, Kapusta acknowledged that, if attempted today, most of the particles would be lost between the injection point and the destination – there is little control over where the particles go.

An indirect environmental and social cost of nanotechnology's deployment to increase oil and gas extraction could be the opening up of new regions for drilling. Nanotechnology is being developed to increase the rates and reduce the costs of oil and gas extraction, to make currently marginal oil reserves economically viable. Areas such as the Arctic and Amazon Basin are home to indigenous peoples who have resisted destruction of their natural environments and way of life for oil and gas extraction. These areas also have high ecological value. To date regions like these have been partially protected from oil and gas drilling by virtue of the higher costs of drilling in remote areas, or of the comparatively smaller amounts of readily recoverable oil. Nanotechnology could change this equation, exposing wild country and the homelands of indigenous peoples to oil and gas exploitation.

Finally, there is an opportunity cost inherent in investment in nano-based petrochemical extractives. More research dollars invested into improving extraction of fossil fuels mean fewer dollars for renewable energy research, or for infrastructure spending to reduce fossil fuel consumption such as more effective public transport.

Health and environmental safety

Some of the nanomaterials developed for use in this sector may pose health and environmental risks. These risks would be particularly acute were tons of nanomaterials to be intentionally released to the environment to track and map hydrocarbon reservoirs.

Nanobatteries

Summary

Lithium ion batteries (Li-ion) have attracted strong interest for their use in electric cars and also to support large-scale energy storage. The use of nanomaterials has enabled the development of Li-ion batteries that are smaller, more efficient and have greater storage capacity. On the other hand, where nanomaterials are used in Li-ion batteries, the energy demands associated with their manufacture may increase the batteries' life cycle impacts. For example production of single walled carbon nanotubes (SWCNT) is more energy intensive than graphite, which is typically used as a Li-ion battery anode. SWCNT production also generates additional carbon dioxide, waste acid and dissolved metals. The incorporation of nanomaterials in Li-ion batteries also increases the energy demands of recycling. Life cycle analysis is required to determine whether or not the use of nanomaterials in Li-ion batteries will deliver net environmental savings or costs. There are also health and environmental concerns regarding some of the nanomaterials proposed for use in Li-ion batteries.

Background

Batteries have a long history; some records indicate that battery technology might have been used as far back as 2000 years ago in the Middle East. Modern 'miniature batteries' were invented in 1950 in the US. These 'alkaline' batteries paved the way towards portable electronic devices, such as portable radios, stereos and other appliances. Today, nanomaterials are being used to improve upon lithium ion (Li-ion) technology, a type of battery that has better energy storage than any other battery on the market. How is nanotechnology claimed to improve existing technology?

Nanotechnology is enabling the commercial production of smaller, lighter, longer lasting, and more powerful batteries. Most research efforts are geared towards creating more efficient and cheaper batteries for electric and hybrid vehicles. Nanomaterial use is also slated for various electronics and to increase the capacity and decrease the recharge/ discharge time of energy stored from renewable sources such as solar and wind devices (Green Car Congress 2009) (ScienceDaily 2009). It is also hoped that nanotechnology could increase the safety of Li-ion batteries, which are vulnerable to overheating and flammability.

> *It is not yet clear whether or not the use of nanomaterials in the production of Li-ion batteries achieves performance gains sufficient to cancel out the greater energy demands and environmental burden of manufacturing the nanomaterials.*

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How is nanotechnology used?

Nanomaterials and their quantum physical properties, such as increased surface to volume ratio and the capacity to absorb lithium have the ability to increase energy densities for Li-ion batteries. In laboratory tests, silicon nanowires can store greater quantities of lithium and can hold a charge ten times greater than normal lithium batteries (Stober 2008).

In other experiments with Li-ion batteries, strong, light-weight and flexible 'carbon nanotube papers' have been used to replace the graphite anodes. Replacing the graphite with the carbon nanotubes increased the battery's capacity threefold (Rochester Institute of Technology n.d.). The researchers also observed that carbon nanotubes have superior thermal and electric conductivity.

Other nanomaterials used in developing next generation batteries include nano lithium iron phosphates, nano titanium oxide, and other nano-metals and nano-crystalline materials.

Altairnano's batteries have a capacity of up to 1MW for larger scale energy storage. These batteries use nano-structured lithium titanate spinel oxide electrode materials to replace the graphite electrode materials found in current Li-ion batteries. The company claims that by using the nano-structured component, there's more surface area available to the ions—up to 100 times more surface area than with conventional, graphite electrodes. This enables the systems to rapidly recharge and discharge large amounts of electricity (Green Car Congress 2009).

Commercial presence

Nanobatteries are already on the market for use in vehicles and in household products, such as power tools.

Nanoparticles and thin films made of high-melting-point materials such as iron and titanium are being used as electrode materials by several Li-ion battery manufacturers, including Valence Technology and Altairnano. The Toshiba Corporation of Japan offers a rechargeable Li-ion battery made from nanoparticles that they claim can recharge in a few minutes and can be discharged and recharged 1,000 times (Toshiba Corporation 2005). DeWalt, a manufacturer of power tools also employs nanomaterials in its products. The company sells rechargeable batteries for their tools that contain NANO™ phosphate lithium ion cells, which they claim can deliver two to three times more run-time compared to their 18V batteries, have a long battery life and durability up to 2,000 recharges (DeWalt 2010).

A company that has garnered a lot of attention is A123 Systems, Inc. in the US, which produces a battery they can install into a Toyota Prius hybrid vehicle, turning the car into a plug-in hybrid. The company claims the car is capable of achieving 100-plus miles per gallon for the first 30 - 40 miles of electrically assisted driving (A123 Systems n.d.). A123 Systems claims this will allow for up to a 60 percent reduction in fuel consumption and greenhouse gas emissions (although the company does not take into account greenhouse gas emissions associated with making the batteries; A123 Systems n.d.). The company provides installation centres throughout North America, where hybrid vehicles can be converted quickly. This is an impressive technology, although life cycle analysis is required in order to establish whether the energy costs of manufacturing these batteries substantially undermine the higher efficiency of the converted car.

A123 Systems also mass produces other patented Nanophosphate™ technology batteries for applications ranging from power tools to grid stabilisation for power stations, such as wind farms. The company claims some of their batteries can "reduce the associated emissions of CO2, SO2, and NOx [carbon dioxide, sulphur dioxide and nitrous oxides] by as much as 80 percent over traditional power plant ancillary services" (A123 Systems n.d.).

Altairnano's 1MW Li-ion batteries are already commercially available (Green Car Congress 2009).

Does nanotechnology deliver?

Nanotechnology has led to improvements in the performance of batteries, as discussed above. However, it is not yet clear whether or not the use of nanomaterials in the production of Li-ion batteries achieves performance gains sufficient to cancel out the greater energy demands and environmental burden of manufacturing the nanomaterials.

Sustainability and life cycle issues

The manufacturing of batteries can be environmentally intensive (US EPA 2008). The addition of nanomaterial components further raises the energy demands of battery manufacture. In a presentation during a meeting of the Organization for Economic Co-operation and Development (OECD), Kathy Hart from the US Environment Protection Agency (EPA) spoke of the need to develop life cycle assessments for nanotechnology applications like those used in Li-ion batteries. Hart warned that "the manufacture of nano-structured materials uses significant amounts of energy, which can result in significant environmental impacts" (Hart 2008).

Researchers caution that where carbon nanotubes are used in Li-ion batteries, "it is difficult to assess whether the performance enhancements in the battery justify the material- and energy-intensive upstream production process" (Seager, Raffaelle and Landi 2008). Life cycle assessment of electric vehicle batteries has found that although lead-acid, nickel-cadmium and nickel-metal hydride batteries have comparable

Embedding nanomaterials in Li-ion batteries may cause problems for recycling.

environmental impacts, the impacts of lithium ion batteries may be lower (Matheys, et al. 2007). However, where nanomaterials are used in Li-ion batteries, the energy demands associated with their manufacture may increase the batteries' life cycle impacts. For example compared with graphite that is typically used as a Li-ion battery anode, production of SWCNT is electricity and/ or fossil fuel intensive, and generates additional carbon dioxide, waste acid and dissolved metals (Sengul, Theis and Ghosh 2008).

The performance of Li-ion batteries which use SWCNT (for example as an anode, in place of graphite) is still largely untested on all but laboratory scales (Seager and Linkov 2009). Whether or not the nanotubes will deliver net environmental savings or costs depends on the environmental impacts of SWCNT production, the quantity of SWCNT in the battery, and the effectiveness of SWCNT in either increasing the number of miles driven per unit of energy input or reducing pollution output (Seager, Raffaelle and Landi 2008). See sections following for a discussion of the demands of nanomaterials manufacturing.

Further, embedding nanomaterials in Li-ion batteries may cause problems for recycling. The operating temperature for the smelting process must be increased substantially to extract nanomaterials fully and to avoid contamination of air, water and recyclable materials. This requires greater energy and results in higher levels of carbon dioxide emissions (Olapiriyakul and Caudill 2009).

Health and environmental safety

The use of nanomaterials such as carbon nanotubes in Li-ion batteries poses health and environmental risks. The health risks associated with carbon nanotubes, in particular their potential to cause mesothelioma and disease similar to that caused by asbestos, have attracted international concern (see health and environment section following).

Silicon nanowires, also being researched for application in Li-ion batteries, are of concern because of their high length to diameter ratio. Few toxicology studies have been conducted on silicon nanowires. However, a study on zebrafish embryos found that silica nanowires were highly and selectively toxic. The study further demonstrated that the silicon nanowires were teratogenic (able to cause birth defects), causing abnormalities and embryonic death (Nelson, et al. 2010).

Nanosupercapacitors

Background

A capacitor differs from a battery in the way it stores energy. Batteries employ a chemical reaction to store energy, while capacitors instead use electrostatic action (the sudden and momentary electric current that flows between two objects at different electrical potentials caused by direct contact or induced by an electrostatic field).

Supercapacitors (also known as ultracapacitors) are between a battery and traditional capacitor in design and performance. They can store energy for shorter periods of time but can charge and discharge very rapidly. Supercapacitors can be used for a wide variety of applications such as cell phones, medical equipment (defibrillators), and in buses that start and stop frequently (Halper 2006). They are not commonly used as a main power supply, but rather to provide power boosts or back-up for batteries, or to bridge short power interruptions, such as in regenerative breaking in hybrid electric vehicles (Buchmann 2010).

Supercapacitors are also potential candidates for improving hybrid electric and other electric vehicles as they can provide a rapid surge of energy to start a vehicle, which cannot be done with normal batteries (Cientifica 2007a). The technology is also suited for storing energy from renewable sources, such as solar and winds (Cientifica 2007a).

How is nanotechnology claimed to improve existing technology?

Supercapacitors can store much more energy and can charge much more quickly than traditional capacitors. This is made possible by their use of nanomaterials that have a high surface area to which the charge is attached (Cientifica 2007a). The charge stored on this massive surface is not subject to the same thermodynamics as battery oxidation-reduction reactions. This means that unlike traditional capacitors or Li-ion batteries, supercapacitors can be recharged hundreds of thousands of times (Woodbank Communications 2005). They can also be much smaller than batteries.

How is nanotechnology used?

Researchers have found ways to create printable thin film supercapacitors constructed from single-walled carbon nanotubes with very high energy and power densities (Kaempgen, et al. 2009). Similar developments have been achieved by US researchers who have been able to produce lightweight, highly flexible batteries and simple supercapacitors by printing on paper (Berger 2009c). The Stanford researchers found that coating a sheet of paper with ink made of carbon nanotubes and silver nanowires makes a highly conductive storage device. They suggest that in the future such applications could be used to power electric cars or to store electricity on the grid.

Other interesting battery developments have come about through nanotechnology research. Researchers at the Massachusetts Institute of Technology (MIT) have gone so far as to manipulate viruses to construct nanowires to make tiny batteries (MIT 2006). Zinc oxide nanowires are also being researched to make nano-generators that could be attached to clothing and designed to charge with body movement or wind. The researchers hope that such clothing could one day power an iPod or other electronic device, although their peers suggest that would be "very difficult to generate an output useful enough to power up devices" (Fildes 2008).

Commercial presence

High initial capital costs of supercapacitors have restrained their uptake; cheaper competing technologies such as batteries have been preferred for applications that require moderate power supply. Nonetheless, utilities are increasingly using devices such as supercapacitors to ensure the continuous supply of power during the period between a power blackout and the resumption of back-up power (Business Wire 2009). Supercapacitors are also slowly entering battery dominated devices such as digital cameras and flashlights.

Analysts suggest that the automotive sector will be the key driver of growth for supercapacitors in the coming decade, especially in hybrid vehicles. Some suggest that advancements in supercapacitor technology could displace the Li-ion battery as the dominant automotive battery technology before 2015 (Business Wire 2009). From 2010 onwards, in automotive sector applications, supercapacitors are expected to experience an annual revenue growth of 50 percent or higher (Business Wire 2009).

Sustainability and life cycle issues

We have not been able to find any life cycle analyses of supercapacitors that use nanomaterials. As discussed in following sections, the energy demands and environmental burden of manufacturing nanomaterials is high.

Health and environmental safety

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Nanocoatings and insulators

How is nanotechnology claimed to improve existing coatings and insulation?

Nanomaterials are used extensively in coatings that repel dirt and generate 'self-cleaning' surfaces for structures, household surfaces and buildings. Other nanocoatings are antimicrobial.

Nanostructured insulation is able to offer more effective insulation. Some nanocoatings are also used to insulate.

How is nanotechnology used?

Nanoscale insulators in the form of aerogels or 'frozen smoke' are extremely light and made of silica. As they are nearly transparent, they can be used in place of glass in skylights and roofing. As these contain countless nanoscale pockets of air, proponents claim they provide two to eight times better insulation than fibreglass or polymer foams (Cientifica 2007a).

Nanocoatings can also be used as insulation; insulation coating is created from a maze of nanoscale tunnels and can slow down heat transfer (Nansulate n.d.). Researchers hope that lighter nanomaterial insulation for cars and airplanes, based on multi-walled carbon nanotubes, could deliver energy savings by increasing fuel efficiency (Lecloux and Luizi 2009).

Nanotechnology based superhydrophobic materials can repel water and prevent icing. This could protect structures and building surfaces from harsh weather and icing (General Electric 2009).

Windows coated with nanomaterials such as nano titanium dioxide can repel dirt and self-clean, reducing cleaning costs. Nanomaterials such as titanium dioxide are also being promoted for their antimicrobial properties.

Other nanopaints can protect buildings and highway structures from dirt, cutting down on maintenance and cleaning (Overs 2009).

Nanomaterial coatings are also being developed as anti-fouling agents and surface treatments for boats. One company claims that its nanocoatings create a barrier against debris and build up on the hulls of boats and ocean vessels (Envere Marine n.d.). One company markets its nano titanium dioxide window applications on the basis that "biological contamination" is reduced and windows are kept clean (Bio Shield Inc. n.d.).

Some manufactures of nanocoatings also claim they can reduce the use of detergents. Numerous silver nano coatings have been introduced with antimicrobial properties including Bactiguard (Bactiguard AB, Sweden), HyProtect (Bio-Gate AG, Germany), Nucryst's nano-crystalline platform technology (Nucryst Pharmaceuticals Corp., USA), Spi-ArgentTM (Spire Corp. USA), Surfacine (Surfacine Development Company LLC, USA), and SylvaGard (AcryMed Inc., USA; Wijnhoven, et al. 2009). These are used as medical antimicrobials in textiles and surface coating products including wall paints, self-sterilising hospital gowns and bedding. Nano silver is also used widely in domestic products such as household cleaning aids, appliances, clothing, mattresses, computer keyboard coatings, food packaging and personal care products.

The use of photocatalytic nanocoatings for concrete pavements has also been mooted in an effort to reduce urban air pollution. By reacting with pollution in the air, the nanocoating is intended to break down harmful substances (Hassan 2010).

Market presence

Nanomaterial coatings are some of the most common nanoproducts on the market. There are nearly 100 examples of nanocoatings listed on the Woodrow Wilson Center's Project on Emerging Nanotechnologies nano consumer products database (Project on Emerging Nanotechnologies 2010). Nanoscale insulators have been on the market since 2003 (Cientifica 2007a).

Does nanotechnology deliver?

Nanocoatings do offer self-cleaning and antibacterial surfaces, although concern has been raised that the growing use of antibacterial coatings could have a negative public health impact (see following section).

Further, life cycle analysis is required to determine whether or not nanocoatings and insulation offer energy and emission savings compared to conventional materials.

It is also unclear whether or not nano insulation offers substantial functional advantage and practical value over existing insulation materials and technologies. A report commissioned by the government of the UK found that nano insulation products that are currently commercially available are "relatively niche" and "do not appear to be replacements for mass insulation" (Oakdene Hollins 2007, 71). The report also noted that the cost of nano insulation applications will remain prohibitive until its environmental implications are assessed and any strong environmental advantage demonstrated. The authors observed that "there is little independent verification of the efficiency of these products so far". Finally, the authors pointed out that although there is much innovation in the insulation sector, not much of it uses nanotechnology.

Sustainability and life cycle issues

There has been inadequate life cycle assessment of the net environmental impacts of using nano-coatings or insulating materials rather than conventional materials. Given the increased energy demands associated with nanomaterials manufacture, and the toxicity concerns associated with both

Nanolubricants

Nanolubricants are also on the market. Israeli company ApNano Materials, Inc. sells engine and gear box lubricants based on "tungsten disulfide fullerene-like nanopowders" (Nanolub n.d.). These can be used in automobiles, aircrafts, and marine equipment, as well as for aerospace applications. The company claims that independent testing shows that its lubricant diminishes engine friction, reducing fuel use in vehicles by more than 5 percent (AzoNano 2009). However, there are no life cycle energy assessments currently available that compare fuel savings with the energy demands of manufacturing the nano lubricant.

nanomaterials and production processes, it is not yet clear whether there is a sustainability advantage in using the nanoproducts.

An early hybrid life cycle assessment of the use of titanium dioxide coatings in concrete to reduce urban air pollution found mixed results (Hassan 2010). Costs included: increase in global warming, fossil fuel depletion, water intake, ozone depletion, and impacts on human health. Benefits included: reduced acidification, eutrophication, air pollutants, and smog formation. The authors conclude that there is a net environmental benefit in using the nanocoating, although other researchers have cautioned that the methodology used may have underestimated the environmental and energy demands of manufacturing the nano titanium dioxide (Khanna and Bakshi 2009).

Environment and health risks

There are health and environmental concerns about nanomaterials used in nanocoatings and surface treatments. On a number of surface types, but especially tiles, coatings containing nano-titanium dioxide have been shown to release nanoparticles when subject to UV light and conditions simulating wind and human contact (Hsu and Chein 2007). Swiss researchers have detected titanium dioxide nanoparticles shed from paint on building exteriors in nearby soil beds and streams (Kaegi, et al. 2008). They found significant releases of titanium dioxide nanoparticles in urban runoff after a rainstorm.

See following sections on the health and environment risks of nanomaterials for a discussion about the potential negative ecological impact of nanomaterials and the potential for disruption by photocatalytic and antibacterial nanomaterials of carbon and nitrogen cycling.

Fuel Catalysts

Background

Catalysts initiate or accelerate chemical reactions without being consumed by them (a process called catalysis). Catalysts added to fuel can result in a more complete combustion of fuel. This can allow a combustion engine to maximise energy extraction while minimising emissions.

How is nanotechnology claimed to improve existing technology?

Nano fuel catalysts could reduce the amount of fuel wasted in car, bus and other vehicle engines. Nanoparticles are attractive ingredients in fuel catalyst because of their increased surface area and heightened surface reactivity. This can make the fuel catalyst more effective using less catalyst material.

Market presence

There are growing numbers of nanoparticle fuel catalysts on the market that claim to improve greater fuel efficiency. The Environ™ Company's nanotechnology based fuel catalyst has been available in the Philippines as of 2005. The company claims that it achieves fuel savings of 8-10 percent and a reduction in emissions of 14 percent (Oxonica 2005).

Fuelstar™ is another manufacturer of nano based fuel catalyst (made of sub oxide tin), based in New Zealand. It claims that its product offers similar efficiency savings for cars, trucks, boats, ships, locomotives, power stations and mining equipment (Fuelstar™ n.d.). The company guarantees 8 percent fuel savings or your money back. The company claims their product is especially helpful in biodiesel fuels that tend to crystallise, for eliminating diesel bacteria in tropical climates, and also prevents gelling of diesel fuel in cold conditions (Fuelstar™ n.d.).

Fuel savings and emission reductions are also noted by other companies, such as Energenics, which recently demonstrated fuel savings of 8-10 percent on a mixed fleet of diesel vehicles in Italy (Cerion Enterprises 2009).

Does nanotechnology deliver?

The use of nano fuel catalysts has resulted in fuel efficiency savings in the order of 8 percent; further, studies on the nano cerium oxide product Envirox have confirmed that it reduces particulate matter and unburned hydrocarbons in vehicle emissions (Park, et al. 2008). This is substantial, but it does not necessarily mean that the catalysts deliver energy and environmental savings overall. None of the companies offer LCA comparisons of the energy and environmental burden associated with production of the nanomaterials compared to the efficiency savings their products are claimed to deliver.

Sustainability and life cycle issues

And as is the case with other nanoproducts, it is unclear whether the energy demands of manufacturing nano catalysts will outweigh the efficiencies in fuel consumption and reductions in emissions.

Environment and health risks

There are concerns that nanometals from fuel catalysts could be emitted in engine exhaust or that nano fuel catalysts could alter the toxicity of other emitted particles. This could pose new risks to people inhaling the particles, or the environmental systems into which emissions are released. In vitro hazard data regarding the potential health or environmental risks of fuel catalysts such as nano cerium oxide is limited and precludes a full assessment of fuel catalysts' health effects (Health Effects Institute 2001; Prospect: Global Nanomaterials Safety 2010).

A recent UK study found that at current levels of exposure to nano cerium oxide as a result of the addition of Envirox to diesel fuel, pulmonary oxidative stress and inflammation are unlikely (Park, et al. 2008). These are the precursors for respiratory and cardiac health problems. The study was conducted by Envirox in conjunction with academics. It is unclear whether higher levels of exposure, associated with greater uptake of such nano fuel catalysts, would pose unacceptable health risks.

Fuel catalyst products in the US must be registered under EPA's "New Fuel and Fuel Additive Registration Regulations," which requires manufacturers to analyze the emissions generated by their product (US EPA 2004). However, it is unclear how effective this regulation is while detection methods for nanoparticles are still in their infancy. It is difficult to imagine that company studies on emissions are able to provide accurate information on nanoparticle emissions.

Reinforced parts for airplanes and cars

How is nanotechnology claimed to improve existing technology?

Proponents hope that by using super strong, stiff and lightweight carbon nanotubes to reinforce car and airplane parts, they can achieve substantial weight savings that reduce fuel consumption.

Market presence

Carbon nanotubes are being used to reinforce specialty parts for planes, cars and high performance plastics, in fuel filters, electronic goods and carbon-lithium batteries (Cientifica 2007a). Although parts of aircrafts and vehicles have been built with carbon nanotubes, the nanocomposites currently on the market lack the structural properties to completely take the place of conventional materials in many applications (Greene 2009).

Nanotechnology applications have not been reported in commercial aircraft airframes until recently. The first application in the general aviation sector was announced in 2008. Avalon Aviation's Giles G-200 (single engine fully acrobatic) flew with Unidym's carbon nanotubes incorporated into its carbon fibre composite engine cowling. The nanotubes provided increased strength and flexibility to combat the effects of aerodynamic stress and engine vibration (Bax & Willems Consulting Venturing 2009).

In 2006 a Canadian nanotube supplier claimed that Boeing was keen to add single walled carbon nanotubes to its lightweight polymer composites to improve structural integrity and provide lightning protection (McCarthy 2006). Ninety percent of the outer structure of the new Boeing 787 consists of lightweight polymer-based composites in an effort to achieve fuel savings. We haven't been able to find updated information about whether or not the nanotubes are in use on commercial Boeing 787 planes.

Does nanotech deliver?

A report for the European Commission concluded that despite the expectations, technical and performance issues meant that nanotechnology had yet to be taken up widely or to deliver efficiencies in vehicles:

> *"… nanotechnology has not significantly contributed to lighter vehicles structures and powertrain systems nor to more efficient or alternative propulsion systems. Failing to meet the full set of industrial requirements (e.g. production volumes, automation and/ or quality assurance) is preventing further deployment into mass-markets whereas stringent performance requirements (e.g. stiffness, strength, wear-resistance) at reasonable cost has limited its use on vehicle parts such as windows or bumpers" (Bax and Willems Consulting Venturing 2009).*

Given the high energy demands of manufacturing carbon nanotubes, the use-phase must be extremely efficient to justify the large energy investment of manufacturing nanomaterials (Seager and Linkov 2009). Early life cycle analysis suggests that it is uncertain whether or not use of carbon nanocomposites will deliver energy savings in cars (see next section).

Boeing has announced its intention to achieve 20% fuel savings in its 787 planes. The use of carbon fibre (not nano) reinforced plastic polymers is reported to have helped it achieve a 3% fuel reduction (Brady and Brady 2007). No information exists regarding whether or not the use of carbon nanotubes could deliver further efficiency savings, or whether the major weight reductions have been achieved without nanotechnology.

A key concern of Friends of the Earth's is that although any net life cycle energy saving and increase in fuel use efficiency will deliver environmental gains (especially in the automotive sector), such gains could be rapidly eroded by growth in the personal and industrial goods transport sector.

Sustainability and life cycle issues

Early life cycle analysis has found that whether or not use of carbon nanofiber composites delivers energy savings in cars depends on certain variables (Khanna and Bakshi 2009). Carbon nanofiber (CNF) composites required 1.6-12 times the energy of steel to produce (Khanna, Bakshi and Lee 2008). Where they are used at lower loadings, 1.4-10 percent savings in lifetime fuel (gasoline) use are predicted. These fuel savings offset the extra energy associated with CNF manufacture, delivering net energy savings. Where CNF are used at higher loading (9-15 percent), their use may result in an overall increase of the fossil energy of the life cycle. Sources of uncertainty in the analysis include: the manufacturing efficiency of CNF, the extent to which nanocomposites can practically replace existing steel panels, whether or not CNF composites offer the required functionality and aesthetics in use, and distance travelled by the car.

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Efforts to achieve widespread use of carbon nanotubes and carbon nanofiber in the automotive and airplane sectors require huge investment and pose substantial safety risks. Safety risks are particularly serious for workers manufacturing the nanotubes and the products in which nanotubes are used. Nonetheless, the efficiency gains may be as little as a few percent. Far greater environmental savings could be achieved by investing in efficient mass transport alternatives to daily commuting by private vehicle and to taking short haul flights, by discouraging the air freighting of perishable foods and by moving goods by rail rather than road or air wherever possible.

Further, the use of nanocomposites could substantially reduce the potential for building materials, car parts or other high performance plastics to be recycled. Separating nanomaterials from the composites in which they are embedded would be far more difficult – and perhaps energetically costly – than recycling the same unit of steel or aluminium.

Health and environment risks

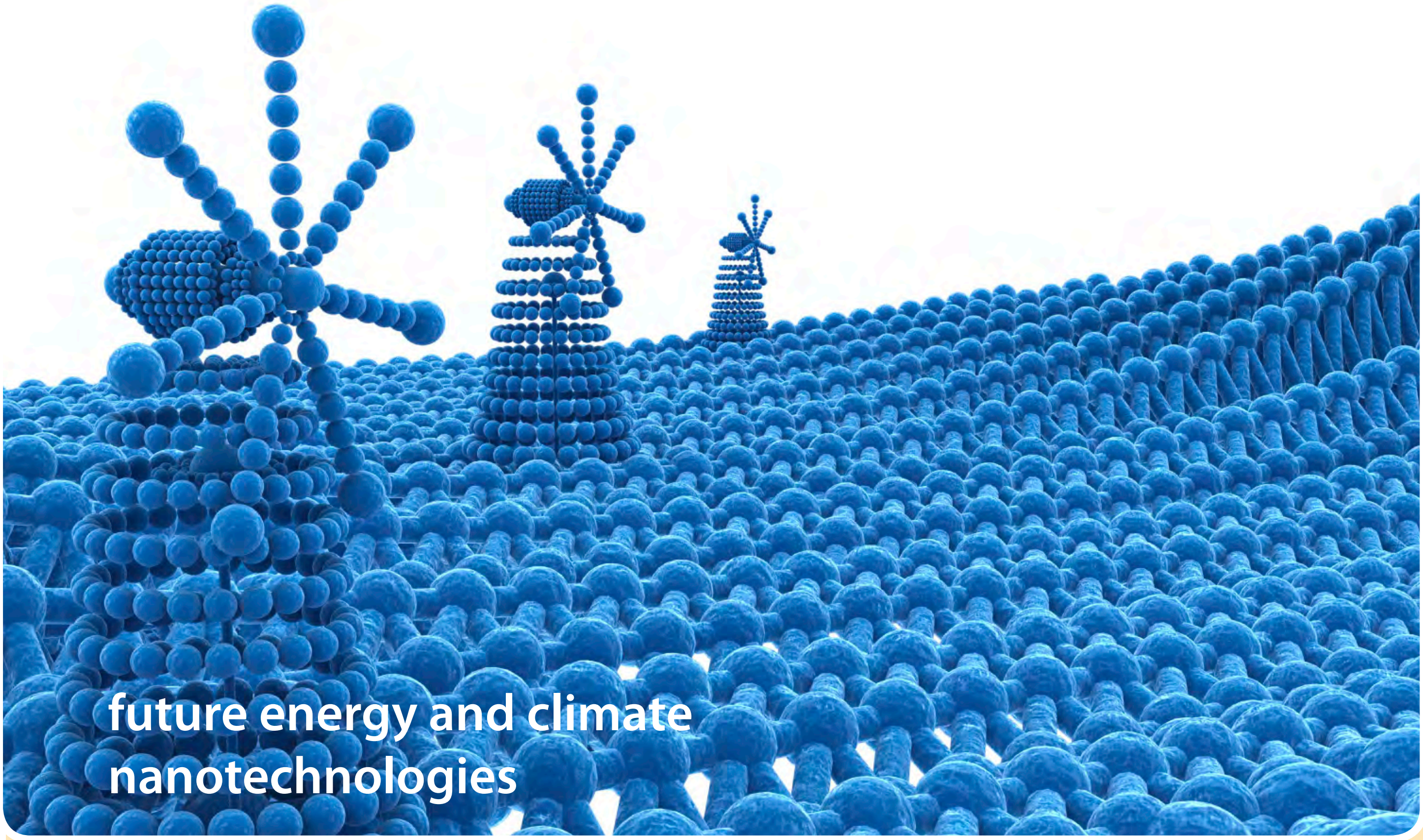
The health and environment risks associated with carbon nanotubes are discussed in detail in sections following. A key concern is that some forms of carbon nanotubes have been shown to cause mesothelioma, the deadly disease associated with asbestos exposure.

most nanoproducts are not being developed for energy savings and will carry a net energy cost

Nanotechnology proponents are keen to point to the potential for nanotechnology to deliver energy savings via applications such as solar cells, lithium-ion batteries for electric cars or lightweight components for airplanes or cars. In many instances it is difficult to establish whether there are in fact energy and environmental savings associated with these products, given the huge energy demands of nanomaterials manufacture, difficulties in recycling nanomaterials and significant uncertainties in conducting accurate life cycle analyses (Olapiriyakul and Caudill 2009; Reijnders 2009; Seager et al. 2008; Seager and Linkov 2009). However, it is seldom acknowledged that most nanoproducts on the market are likely to come at a net energy cost because they offer no potential during their use to recoup the huge energy investment associated with manufacturing the nanomaterials.

There are substantially greater numbers of nanoproducts on the market that offer no potential for energy savings than those that do. The nanoproducts that dominate current sales and product inventories, such as cosmetics and personal care products, are not only energy intensive to manufacture, but offer no potential for energy savings through their use. This is true of many – if not most – nanoproducts on the market, such as diet products, toothpastes, food additives, supplements, clothing, food packaging, cutlery, baby toys, household cleaning products, golf clubs and tennis racquets, antibacterial computer mouse pads and keyboards, and high performance televisions. "As is typical of rapidly growing industries, nanotechnology manufacturers are more focused on maximising production and technological development than on environmental efficiency or sustainability" (Seager and Linkov 2009, 426).

In 2004 the UK Royal Society estimated that the skincare products sector was the biggest commercial user of manufactured nanoparticles – at least two orders of magnitude ahead of structural or environmental applications, information and communication technologies, or other sectors (UK RS/RAE 2004, 27). The product inventory maintained by the US Woodrow Wilson Center's Project on Emerging Nanotechnologies is not comprehensive and lists only products whose manufacturers identify nano content in their products. Nonetheless, it is interesting to note that in 2010, the inventory remains dominated by health and fitness nanoproducts, particularly cosmetics and personal care products (Project on Emerging Nanotechnologies 2010).



future energy and climate nanotechnologies

Nano solar has been predicted to deliver game changing functionalities and applications, for example spray on, energy generating plastic-based paint that can harvest infrared light five times more effectively than current solar cell technology (Lovgren 2005). However, most of these 'breakthrough' applications, along with the predicted dramatic efficiency gains or cost savings, remain at early laboratory or 'proof of concept' stages, far from being anywhere near practical applications. Whether or not such applications will be practically achieved – and what sort of time frame it will entail – remains uncertain.

Nanotechnology has a sort of science fiction quality to it, and proponents predict there will be a mass of future products that make it seem even more so. Things like tiny batteries made from viruses; 'nano antennas' and 'nanowires' able to capture energy from wind, sun and body movement to be used in clothing, camping equipment and hand bags; infrared-harvesting, plastic-based paint; and supercapacitors that will make our electronic devices incredibly small and our cars more efficient. Most of these technologies are still at a laboratory stage of development. Only a few such products are available to the (affluent) shopper, such as Konarka's range of travel wear which incorporates small solar panels for recharging laptops or mobile phones.

An application that has consistently captured the imagination of the science community is nano-based infrared light generators. Infrared light, which has a longer wavelength than visible light, is impossible for the human eye to see, although we can feel it as heat. More than half of the light emitted from the sun is infrared and holds the potential to generate electricity similarly to the harvesting of UV and other visible light forms through solar panels. Infrared radiation can also be emitted from just about anything -- people, the ground, machines, engines, and factories to name a few.

Nano antennas have been constructed to capture infrared rays and turn them into electricity. Metal nanoparticles such as gold can be used to create tiny antennas, which can be printed on to sheets of plastic to produce electricity (Stricker 2008). Researchers hope that this technology could eventually help create solar panels that are able to collect energy from the sun during the night or in adverse weather conditions. However, although the antennas are currently very good at capturing the sun's energy, they are not very effective at converting it. Nonetheless, a physicist who spearheaded this technology at the Idaho National Laboratory hopes that once they overcome these technical challenges, the antennas could have the potential to replace traditional solar panels. He suggests that in the future antenna-based panels could be used to create portable battery packs and could even be imbedded into clothing (Stricker 2008).

Silicon nanowires may enable development of cheap thermoelectric devices that convert heat into electricity. This technology is predicted to require another 10 years of development (President's Council of Advisors on Science and Technology 2010). The University of California, San Diego (UCSD) has produced a similar technology. Their nanowires, built from indium phosphide, can increase the efficiency of plastic thin film solar cells (UCSD 2008).

Nanoscale has also inspired highly futuristic wind energy concepts. A Mexican designer has developed the concept of using nanoscale wind turbines to create 'Nano Vent-Skin,' basically a thin covering of nanoscale wind turbines that connect with other photovoltaic systems. The wind turbines measure only 25mm by 10.8mm. The hope is that they can be placed on buildings and other edifices to generate power, for example if placed along the inside of railway tunnels the turbines could use the wind of a passing train to power the lights of the next station (Otegui 2008).

'Breakthrough' promises versus real-life barriers

Critically reviewing the barriers to nanotechnology product development and commercialisation is essential for two key reasons. Firstly, the urgency of climate change demands that we act now to cut emissions. If nanotechnology products and applications are not going to provide certain and rapid solutions, we should instead focus on the practical and policy measures that will. Secondly, we must question the opportunity cost of continuing to direct large quantities of public funding into nanotechnology research when other sectors, for example mitigation measures, go begging for funds.

Many predictions regarding nanotechnology's capacity to deliver 'breakthrough' energy and climate benefits are based on applications that are still at a laboratory prototype stage. It is difficult to determine whether these products will work in the real world and on a large scale, or whether they'll remain intriguing but unviable ideas. However, such an examination is absolutely essential to deciding whether the huge hype – and public funding of research and development – for energy applications that use nano is warranted.

There are strong commercial incentives for industry to exaggerate the positive social and environmental effects of nanotechnology and to understate the technical or commercial obstacles to successful product development. Nanotechnology proponents put forth any number of promises in order to persuade target audiences and to mobilise resources to support industry development (Shelley-Egan 2010). However, pursuit of this 'hype strategy,' based on inflated promises, can direct investment into unfeasible areas of research rather than more practical fields (Shelley-Egan 2010).

Many proponents, including scientists, have predicted rapid commercialisation of nanotechnology breakthroughs on the basis of extremely early stage, laboratory based work. Some researchers have cautioned that in the promotion of nano solar, manufacturing constraints and barriers are commonly ignored, and much of the work in the published literature is based on unrealistic expectations (Gupta, et al. 2009). Lux Research analyst Kristin Abkemeier emphasises that the scaling up problems experienced by nano solar are not isolated: "The same is true with other nanotechnologies; it's not happening as soon as people thought it would" (Lubick 2009).

The CEO of nanotechnology analyst Cientifica has cautioned that practical barriers against taking a research discovery and turning it into a viable nano product are significant: "The companies using nanotechnology to produce thin film solar systems have burned through a quarter of a billion dollars of venture capital money over six years, and still haven't cracked the manufacturing and reliability issues which will make the technology economic" (Harper 2007).

Enormous financial resources are directed to nanotechnology's energy and environmental applications. In 2008, this sector accounted for 29 percent of all nanotechnology funding by the US Federal Government, 14 percent of all US corporate nanotechnology funding and 41 percent of US venture capital funding. Further, energy and environmental applications were the subject of 21 percent of nanotechnology publications and 59 percent of all nanotechnology patents (President's Council of Advisors on Science and Technology 2010). Yet the same year only 1 percent of actual nanotechnology-based products came from the energy and environmental sector, including items such as nano-enabled filtration membranes or batteries (President's Council of Advisors on Science and Technology 2010). The US President's Council of Advisors on Science and Technology (PCAST) foresees that the majority of nanotechnology applications with biggest potential energy and environmental benefits remain at "embryonic or proof-of-concept stages and have not yet begun a trajectory toward the marketplace."

In addition to the fundamental technical challenges, key barriers in the commercialisation of energy and climate nanotechnologies include: a high cost of production (including potentially to the environment), lagging efficiency and reliability, and toxicity (Ulrich and Loeffler 2006). There are many steps involved in bringing a new technology to market. From an invention or research discovery, research begins in the laboratory to create a laboratory prototype, which can then move to the industrial demonstrator stage where results can be introduced to companies, who can then bring the product to industrialisation, which in turn can lead to market entry of the technology (Ulrich and Loeffler 2006).

Whether or not research and development of certain energy technologies receives funding will often be up to governments. The PCAST report supports observations made by nanotechnology analyst Lux Research that the private sector is increasingly reluctant to be involved in nanotechnology research and development that has a long commercialisation trajectory. "Venture capitalists are increasingly averse to areas of nanotechnology that have long times to market and high capital requirements... As a result, there is a need for novel approaches and funding mechanisms to support the transfer of technologies with long incubation times from the laboratory to the market" (President's Council of Advisors on Science and Technology 2010, 27).

Huge amounts of public funding are already invested in nanotechnology research and development in the energy and environment sectors. Without rigorous life cycle analysis it is very possible that this money will be devoted to applications that offer negligible or no environmental savings, while imposing a new generation of environmental and health hazards.

Huge amounts of public funding are already invested in nanotechnology research and development in the energy and environment sectors. Without rigorous life cycle analysis it is very possible that this money will be devoted to applications that offer negligible or no environmental savings, while imposing a new generation of environmental and health hazards. Scarce public funding is being made available to directly tackle climate change through practical, low-risk measures that could deliver outcomes now; the research funding poured into nanotechnology could come at a high opportunity cost.

does nanotechnology deliver?

To put into perspective the hype around nanotechnology's potential to save us from dangerous climate change, nanotechnology analyst Cientifica predicted in 2007 that "taken as a whole, the use of nanotechnologies can contribute to the reduction of global CO_2 [carbon dioxide] emissions in 2010 by 0.00027%"(Cientifica 2007b, 6).

In their 2008 report, the UK Royal Commission on Environmental Pollution recognised that nanotechnology's potential benefits had been overstated, that taking many nano applications from the laboratory to a commercial scale was proving very difficult, and that the energy demands, low yields and waste associated with nanomaterials manufacture were significant problems (UK RCEP 2008). The Royal Commission also emphasised that the potential for nanomaterials to pose serious new toxicity risks remained uncertain.

Friends of the Earth shares these concerns that in critical areas, nanotechnology doesn't deliver.

Energy demands of nanomanufacturing

The manufacture of nanomaterials is extremely energy intensive and has a high ecological footprint. This is related to: highly specialised production environments, high energy and water demands of processing, low yields, high waste generation, the production and use of greenhouse gases such as methane and the use of toxic chemicals and solvents (Eckelman, Zimmerman and Anastas 2008; Khanna et al. 2008; Sengul et al. 2008).

Carbon nanotubes are touted as one of the most 'promising' nanomaterials for energy savings applications. Yet American researchers who

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Why does it take so much energy to produce nanomaterials? The example of single walled carbon nanotubes (SWCNT)

Synthesis of SWCNT usually occurs in conditions of extreme heat. The general approach involves extremely high temperatures to vapourise a carbon source impregnated with metal catalyst in an inert environment (Seager, Raffaelle and Landi 2008). There are different techniques: arc discharge and carbon vaporization occur at thousands of degrees Celsius, while catalytic chemical vapor deposition (CVD) takes place at the relatively lower temperatures of 500 to 1000°C (Sengul, Theis and Ghosh 2008).

As the vapour cools, some carbon condenses into SWCNT, while the rest remains as carbon soot and waste products, some of it nano-structured. The inability to manufacture SWCNT precisely and the commonly low yields are a key problem (Reijnders 2009). Less than 10 percent by mass of the carbon vapourised may produce SWCNT (Seager, Raffaelle and Landi 2008).

After synthesis comes 'purification'. Even so-called high purity SWCNT may contain a large fraction of simpler forms of carbon or even metal contaminants. Depending on the end use, extensive purification may be required. First a strong acid wash is used to remove metals. Secondly, temperature is used to oxidise the simpler carbon to carbon dioxide, while retaining the SWCNT. Purification after synthesis can increase the energy demands of manufacture by up to 50 percent (Gutowski, Liow and Sekulic 2010).

evaluated the energy and exergy requirements for manufacturing carbon nanotubes concluded that single walled carbon nanotubes may be "one of the most energy intensive materials known to humankind" (Gutowski, Liow and Sekulic 2010).

Different nanomaterials require varying amounts of energy to manufacture. This is affected by feedstock materials (materials from which nanomaterials are produced) and production processes. There is also considerable variation in the reporting of manufacturing energy demands (Gutowski, Liow and Sekulic 2010). Despite this, various analyses have concluded that manufacturing nanoparticles is much more energy intensive than their non-nano counterparts (Tables 4 and 5).

Life cycle energy requirements for carbon nanofibers are 13 to 50 times those of primary aluminium used for smelting (an extremely energy intensive material) and 95-360 times those of steel, based on equal mass (Khanna, Bakshi and Lee 2008). The argument has been made that as the manufacturing sector matures, substantive efficiency savings will be achieved in manufacturing carbon nanotubes and other nanomaterials. However, even assuming a highly optimistic tenfold increase in efficiency, carbon nanofibers would still be three to ten times more energy intensive by mass than aluminium and steel (Khanna, Bakshi and Lee 2008). Kushnir and Sanden (2008) calculated that fullerenes and carbon nanotubes were two to 100 times more energy intensive to produce than aluminium, even using idealised production models. Sengul et al. (2008) evaluated the energy demands of nanomanufacturing integrated nano-circuits, nano-devices for electronics, nanotubes, nanowires and nanorods, quantum dots, fullerenes and dendrimers and found them to be extremely high, in addition to having high waste to product ratios.

In a survey of life cycle impacts of nanomaterials, the energy demands of milling processes for titanium dioxide were found to require significantly less energy than the more specialty processes associated with manufacturing carbon nanofibers or semiconductors (Meyer, Curran and Gonzalez 2009). Nonetheless, production of titanium dioxide nanoparticles results in 3-6 times more carbon dioxide equivalent emissions per kg than bulk form titanium dioxide (Osterwalder, et al. 2006). As much as 60kWh/kg and 16kWh/kg may be required for production of titanium and magnesium nanoparticles, respectively (Donaldson and Cordes 2005). Further, this milling process is not suitable for nano components that require surface functionalisation or specialty blending, which require more intricate manufacturing.

The huge energy demands of manufacturing nanoparticles are exacerbated by the sometimes extremely low yields of production. Although proponents emphasise nanotechnology's capacity for precision, these claims are not matched by reality. "In contrast to the suggestion that the precision of nanotechnology is conducive to eliminating waste products, processes for producing nanoparticles with narrow product specification often generate relatively large nanoparticulate non-product outputs" (Reijnders 2008, 299).

Dry synthesis methods for nanoparticle production (for example grinding down larger particles) yield poor particle size distributions that are vulnerable to contamination (Meyer, Curran and Gonzalez 2009). An inability to control manufacturing to achieve required diameters and lengths results in carbon nanofiber yields that are only 10-30 percent of the feedstock (Khanna, Bakshi and Lee 2008). Sengul et al. (2008) report highly variable yields for carbon nanotube production, from 20-100 percent for chemical vapour deposition processes, around 30 percent for arc discharge and up to 70 percent for laser ablation. However, in some cases less than 10 percent (by mass) of carbon input may produce single walled carbon nanotubes (SWCNT; Seager, Raffaelle and Landi 2008). Up to 90 percent of fullerenes produced may be sent to landfill because they have defects (RCEP 2008).

The variability of nanomaterials produced by different manufacturers can be large; many scientists have already experienced this and have also noted the batch to batch variation from single manufacturers (Klaine, et al. 2008). Large quantities of waste or defective materials are produced, some of which contains nanomaterials or their byproducts, which may be hazardous (Som, et al. 2010).

1 kg of carbon nanotubes may embody the energy of 167 barrels of oil

Based on their review, Gutowski *et al.* (2010) suggest that "it is quite reasonable to expect an order of magnitude estimate of the embodied energy requirements for carbon nanotubes to be in the region of 0.1 – 1 TJ/ kg". One terajoule is one trillion joules. To put this into perspective, consider that it is the equivalent of the chemical energy found in about 167 barrels of oil. Or to put it another way, a woman's weight (63kg) in carbon nanotubes would embody the same energy as the atomic bomb that exploded over Hiroshima (63 TJ).

Table 5: Energy demands and environmental costs of manufacturing nanomaterials

Nanomaterial	Type of analysis, any constraints	Energy demands	Other environmental costs or benefits?	Study authors
Titanium dioxide nanoparticles	Energy, exergy and life cycle analysis were conducted on the Altair titanium dioxide nanoparticle hydrochloride process. Emissions associated with the supply chain of material and energy flows originating outside the process boundaries were not included. Energy required to obtain the ore was not included. EHS impacts of titanium dioxide nanoparticles not included.	The gross energy demands of manufacturing 40nm titanium dioxide nanoparticles were calculated to be close to 7,000 MJ/ hour, where 97kg of titanium dioxide nanoparticles were produced per hour. Distillation and spray hydrolysis were the most energy demanding; distillation requires 4,515.96 MJ/ hour.	The carbon dioxide emitted from the combustion of methane represents the largest contribution to global warming of the process. Hydrochloric acid used in the process is a potential health risk.	(Grubb and Bakshi 2008)
Single walled carbon nanotubes	Life cycle analysis of three established synthesis methods. Use and end-of-life phase are not considered. Health and environmental effects of single-walled carbon nanotubes were excluded. Authors note near absence of EHS data.	Environmental impacts from energy used in manufacture were approximately four orders of magnitude greater than for the other emissions. Although electricity use costs were only 1 percent of base case manufacturing costs, they contributed to 99 percent of environmental impacts.	Impacts considered were climate change, eutrophication, acidification, land use, mineral depletion, ecotoxicity, ozone layer depletion, carcinogens, airborne organics and inorganics. Non-energy emissions generated by the chemical vapor deposition method were an order of magnitude greater than the arc ablation or high pressure carbon monoxide synthesis methods. 40.62g of methane gas was generated for every gram of single walled carbon nanotube produced.	(Healy, Dahlben and Isaacs 2008)
Single-walled carbon nanotubes	Life cycle cradle to gate energy and environmental impact analysis for single-walled carbon nanotubes produced using a range of synthesis methods (CVD, arc ablation and HiPCo). No consideration of EHS impacts of SWCNT themselves.	SWNT synthesis is hugely intensive – 1,440,000 to 2,800,000 MJ per kilogram of SWNTs produced.	CVD had the greatest negative EHS impact, with strongly negative outcomes for 9 of 13 categories assessed. Arc ablation had the lowest.	(Isaacs, Tanwani and Healy 2006)
Carbon nanofiber	Life cycle cradle to gate energy and environmental impact analysis for vapor grown carbon nanofibers produced using a range of feedstocks. Comparison made to steel, aluminum and polypropylene on an equal mass basis. Authors note that most of the synthesis data "are either missing or proprietary" so careful assumptions were made. Several aspects were not included due to lack of reliable data, meaning that LCA results will represent only conservative lower bound estimates. Health and environmental impacts of CNFs were omitted due to lack of data.	Life cycle energy demands range from 2, 872 MJ/ kg for benzene feedstock to 10, 925 MJ/ kg for methane. Requirements for aluminum, steel and polypropylene are 218, 30 and 119 MJ/kg respectively. That is, on an equal mass basis, CNFs were 13 – 50 times more energy intensive than primary aluminum – a very energy intensive material. Even a tenfold potential future decrease in CNF life cycle energy requirements would mean they required 3 – 10 times more energy to produce than steel or aluminum on an equal mass basis.	CNF production has the highest environmental burden in all categories assessed: ozone layer depletion, radiation, climate change, respiratory inorganics, respiratory organics, carcinogens, land use, acidification and eutrophication, ecotoxicity and use of fossil fuels. The global warming potential of 1kg of CNFs is equivalent to 65kg of aluminum or 47kg of steel.	(Khanna, Bakshi and Lee 2008)
Carbon nanoparticles (fullerenes and nanotubes)	Energy requirements for cradle to gate are assessed for a range of synthesis methods (all energy flows up to nanomaterial production and purification). Use and end-of-life phase are not considered. Energy or material flows for capital infrastructure are not considered. Authors note that for several aspects of synthesis there is insufficient information for accurate estimates.	Carbon nanoparticles were 2 to 100 times more energy intensive than aluminum on an equal mass basis, even with idealised production models.	Not addressed. Some synthesis methods use methane, benzene or carbon monoxide as feedstocks, or require large quantities of solvent.	(Kushnir and Sanden 2008)
Various oxide nanoparticles	Cradle to gate analysis of energy requirements, CO2 equivalent emissions and economic costs for wet and dry methods for oxide nanoparticle synthesis. Khanna et al. (2008a) note that due to omissions or approximations of data relating to the energy demands, release and impact of emissions of nanomanufacturing, the LCA accuracy is limited.	Plasma processes, required for manufacturing complex oxide nanoparticles, or heavier particles, such as zirconia, are very energy intensive.	Production of nanoparticle titanium dioxide results in 3 – 6 times more carbon dioxide equivalent emissions per kg produced than bulk form titanium dioxide. Multi-step 'wet' processes are suitable for light elements such as titania, but although these processes use less energy, they require large amounts of toxic solvents.	(Osterwalder, et al. 2006)

Environmental footprint of nanomanufacturing

The energy demands of nanomaterials manufacture, and the life cycle energy efficiency of nanoproducts, are only one component of their ecological footprint. The global warming potential of manufacturing, the chemical burden of manufacturing, the huge water demands of production, the impact of manufacturing on resource depletion and land use, occupational exposure to both nanomaterials and other toxic chemicals used in manufacturing, public exposure to nanomaterials during product use, and the release of both nanomaterials and other toxic byproducts into the environment all contribute to nanomaterials' life cycle environmental burden (Khanna et al. 2008; Meyer et al. 2009; Sengul et al. 2008).

Life cycle analysis (LCA) is intended to be a comprehensive tool for environmental sustainability assessment (Som, et al. 2010). Unfortunately because of the significant uncertainties with the health and environmental risks associated with nanomaterials, and with the end-of-life recycling and disposal, most life cycle analyses that have been carried out to date on nanoproducts exclude these risks from analysis (Healy, Dahlben and Isaacs 2008; Khanna, et al. 2008; Khanna and Bakshi, 2009; Merugula, et al. 2010; see below).

Greenhouse gas emissions of the life cycle of nanomaterials are in part related to the energy demands of manufacture, as most energy supplies are heavily reliant on fossil fuels (Gutowski, et al. 2010; Healy, et al. 2008). Several studies have found that many nanomaterial manufacturing processes for fullerenes, carbon nanotubes and titanium dioxide nanoparticles are not only very energy intensive but also use and release hydrocarbons such as methane (Grubb and Bakshi 2008; Khanna et al. 2008a; Kushnir and Sanden 2008; Merugula, et al. 2010; Meyer et al. 2009; Sengul et al. 2008). The reliance of some nanomaterials manufacturing processes on methane as a feedstock is a key contributor to their global warming potential (Grubb and Bakshi 2008).

Many nanomaterials manufacturing processes use large quantities of toxic, basic or acidic chemicals and organic solvents. Many of these chemicals are persistent (do not readily break down in our bodies or in the environment), accumulate in the body and are toxic (Sengul, Theis and Ghosh 2008). Aromatic hydrocarbons, chemicals which have these characteristics, are used as precursors for the growth of carbon nanotubes and are also formed as byproducts. Emissions of 15 different aromatic hydrocarbons have been identified (Sengul, Theis and Ghosh 2008). The production of titanium dioxide nanoparticles uses large amounts of either sulphuric or hydrochloric acid (Grubb and Bakshi 2008). In conventional methods for purification of nanoparticles such as gold, used for example in dialysis extraction, centrifugation or chromatography, as much as 15 litres of solvent may be used per gram of nanoparticle produced (Sweeney, Woehrle and Hutchison 2006). Production of fullerenes and carbon nanotubes results in a high proportion of waste that contains a variety of carbon structures

One assessment of single walled carbon nanotube (SWCNT) manufacture found that 40.62g of methane gas were generated for every one gram of SWCNT produced (Healy, Dahlben and Isaacs 2008). The global warming potential of methane is 56 times that of carbon dioxide over a 20 year time frame, and 21 times that of carbon dioxide over a 100 year time frame (UNFCCC n.d.)

(Som, et al. 2010). There has not been a full characterisation of the substances in such wastes and it is not clear how to dispose of them safely – or whether they can be disposed of safely. Nonetheless, the byproducts of manufacturing carbon nanotubes have proven to be toxic to aquatic organisms (Templeton, et al. 2006).

The manufacturing of nanomaterials may also drive resource depletion. Sengul et al. (2008) cite Mazurek (1999)'s estimation that 99.9 percent of materials used to manufacture one dimensional nanoproducts used in computers and electronic goods are not contained in the final products, but become waste products. They further observe that: "Many of the materials used in nanomanufacturing are rare, with demand sometimes exceeding production. This raises concerns about availability, price and the suitability of substitutes" (Sengul, Theis and Ghosh 2008, 352). Dutch researchers argue that because thin film nano solar based on cadmium telluride and CIGS is reliant on scare minerals such as indium and gallium, these technologies will never be able to contribute more than 2 percent of global energy demand, due to resource constraints (Kleijn and van der Voet 2010). The United Nations Environment Programme suggests that without rapid efforts to dramatically boost the recovery of rare metals from products at end of life, many high tech applications face resource constraints in the near future (UNEP 2010a).

Health risks of nanomaterials

The gaps in our understanding of nanomaterials' biological behaviour and of their new toxicity risks are large; our capacity to measure, assess, compare and mitigate these risks is in its infancy. Researchers at the Technical University of Denmark have recognised that "knowledge gaps pervade nearly all aspects of basic EHS [Environmental, Health, and Safety] knowledge, with a well recognised need for improved testing procedures and equipment, human and environmental effect and exposure assessments and full characterisation of NM [nanomaterials]" (Grieger, Hansen and Baun 2009).

The European Food Safety Authority has stated clearly that the extent of uncertainty is such that design of reliable risk assessment systems for nanomaterials is not yet possible: "Under these circumstances, any individual risk assessment is likely to be subject to a high degree of uncertainty. This situation will remain so until more data on and experience with testing of ENMs [engineered nanomaterials] become available"(EFSA 2009, 2-39).

Community groups and scientists calling for urgent research into the health and safety of nanomaterials have been joined by some industry members. During a recent Nano Renewable Energy Summit in Denver, Jim Hussey, the CEO of biomaterials company NanoInk and board member of the NanoBusiness Alliance, told the New Haven Independent that: "There are no good, well-controlled studies to prove the safety of our nanomaterials…Frankly, we have none. We need to lead the world in environmental health and safety nanotech testing. We either get ahead of this or it will roll over us as an industry… There is no question that the invasion of cells by nanoparticles could be carcinogenic" (Motavalli 2010).

As particle size decreases, in many nanoparticles the production of free radicals increases; the production of free radicals is a key mechanism for nanotoxicity. Test tube studies have shown that some nanoparticles now in commercial use are toxic to cells (Gerloff, et al. 2009), can damage DNA (Xu, et al. 2009), negatively affect protein expression (Chen, et al. 2008a), nucleate protein fibrillation (Linse, et al. 2007), and cause programmed cell death (Hussain, et al. 2010). Mice studies have found that nanoscale titanium dioxide, touted for use in many energy applications, use can cause genetic instability (Trouiller, et al. 2009) and can pass from pregnant mice to their offspring, damaging their genital and cranial nerve systems (Takeda, et al. 2009). The transfer of fullerenes from pregnant mice to their offspring has also been demonstrated, severely disrupting development of embryos (Tsuchiya, et al. 1996).

Particularly high concerns exist regarding the potential for exposure to nanotubes to cause mesothelioma. The UK's Royal Society (UK RS/RAE 2004) and risk specialists at the world's second largest reinsurance agent (Swiss Re 2004) have warned that carbon nanotubes may behave like asbestos once in the lungs. Since then, a series of in vivo experiments have demonstrated that when introduced into the lungs of rodents, carbon nanotubes cause inflammation, granuloma development, fibrosis (Lam, et al. 2004; Muller, et al. 2005; Shvedova, et al. 2005), artery 'plaque' responsible for heart attacks and DNA damage (Li, et al. 2007). Early studies have shown that some forms of carbon nanotubes can also cause the onset of mesothelioma – cancer previously thought to be only associated with asbestos exposure (Poland, et al. 2008; Sakamoto, et al. 2009).

In addition to the ecological concerns associated with burgeoning use of nano-antimicrobials, there could be a public health cost. Microbiologists and hospital managers have voiced their fears that increasing use of powerful nano- antibacterials in every day consumer products could promote more rapid development of bacterial resistance to nano silver (AM 2009; Salleh 2009). "The wide and uncontrolled use of silver products may result in more bacteria developing resistance, analogous to the world-wide emergence of antibiotic-and other biocide-resistant bacteria" (Silver 2003, 350). This could diminish the utility of nano silver as a medical aid, where it is increasingly used as an alternative to antibiotics to which bacterial resistance already exists. Some reviewers have suggested that clinical bacterial resistance to silver is low and can be managed effectively (Chopra 2007). However, others have cautioned that resistance may already be widespread but undetected (Silver, Phung and Silver 2006). A random collection of enteric (gut) bacteria from a Chicago hospital found that 14 percent had genes for silver resistance (Silver 2003).

The potential for nanomaterials to accumulate in the body is a particular concern. Transfer of nanomaterials such as quantum dots between species of different levels of the food chain

The most common nanomaterial in products can produce significant GHG emissions

Nano silver is reported to be the most common nanomaterial in products; it is frequently used in odour-killing socks and clothing, but also in washing machines, mattresses, kitchenware and other household products. A report in *New Scientist* suggests that its burgeoning use in antibacterial applications could be coming at a huge climate cost. In addition to the energy required to create nano silver, exposure of sludge similar to that found in waste water treatment plants to silver nanoparticles resulted in four times the release of nitrous oxide (Knight, 2010). The United Nations Framework Convention on Climate Change (UNFCCC) considers nitrous oxide to be 310 times more effective at trapping heat in the atmosphere when compared to carbon dioxide over a 100-year time period, which makes it an extremely potent greenhouse gas (UNFCCC n.d.). The public should be made aware that avoiding these types of products can reduce their carbon footprint. Labelling laws are required to ensure people's right to choose nano silver-free products. Equally importantly, regulations should require a greenhouse gas emissions assessment alongside a basic safety assessment, to ensure that climate damaging products are not brought to market.

(trophic levels) has been demonstrated (Bouldin, et al. 2008). In its annual report, the University of California's Center for Environmental Implications of Nanotechnology (UC CEIN 2010) notes that its researchers have found substantive evidence of nanomaterials' bioaccumulation. Their initial experiments have shown that titanium dioxide stimulates the growth of a wide range of freshwater algae, leading to accumulation of titanium dioxide in the tissues of higher trophic levels. Other studies examining the effects of exposure to cadmium selenium quantum dots showed that accumulation and magnification occurs at lower trophic levels (bacteria and protozoa). The report warned that this could mean an even more extreme condition at higher trophic levels, including fish and mammals (UC CEIN 2010).

Many nano solar applications now use quantum dots with cadmium cores, or cadmium telluride films. An inhalation study using rats found that cadmium telluride was far less toxic than cadmium itself (Zayed and Philippe 2009). Nonetheless cadmium telluride is toxic to human breast cells and to prostate cells in vitro (L. Liu, J. Zhang, et al. 2008). Quantum dots have been shown to cause acute cytotoxicity to liver cells (Derfus, Chan and Bhatia 2004) and skin cells in in vitro studies (Ryman-Rasmussen, Riviere and Monteiro-Riviere 2007). These studies showed that the presence of surface coatings can substantially reduce quantum dot toxicity, although another study found that poly-L-lysine coatings increased toxicity (King-Heiden, et al. 2009). However the long term persistence of coatings in the environment and in animals is poorly understood.

An in vivo mice study has shown that 8.6 percent of quantum dots remained in the liver five days after intravenous exposure, from where clearance was difficult; this suggested that long term persistence of small fractions of the quantum dots may occur (Chen, et al. 2008b). In their study of quantum dot transfer from green algae to daphnids, Bouldin and colleagues observed that: "coatings present on nanocrystals provide protection from metal toxicity during laboratory exposures but that the transfer of core metals from intact nanocrystals may occur at levels well above toxic threshold values, indicating the potential exposure of higher trophic levels" (Bouldin, et al. 2008, 1958). A study on zebrafish embryos found that quantum dots were more toxic than exposure to cadmium ions alone (King-Heiden, et al. 2009). The researchers attributed this to both the in vivo partial breakdown of coatings allowing release of cadmium ions, oxidative stress associated with the production of ROS by the quantum dots, and toxicity of other quantum dot components.

Environmental release of nanomaterials could pose risks to not only environmental systems, but also to human health. Som et al. (2010) warn that health risks associated with indirect exposure of humans to nanoparticles in the environment cannot be ignored. They give the cautionary example of children facing harmful lead exposure through uptake of soil and dust contaminated by lead-based paints falling off walls and facades.

Environmental risks of nanomaterials

There is a serious paucity of nano-ecotoxicological data. However, a review of the literature regarding toxicity to aquatic invertebrates concluded that "the limited number of studies has indicated acute toxicity in the low mgl-1 [milligrams per litre] range and higher of engineered nanoparticles to aquatic invertebrates, although some indications of chronic toxicity and behavioural changes have also been described at concentrations in the high µgl-1 [micrograms per litre] range" (Baun, et al. 2008b, 387). Early studies have revealed that nanoparticles of zinc oxide are very toxic to the development of sea urchin embryos. Effects are

seen at concentrations that are approximately 10-100 times smaller than those previously reported for aquatic systems (UC CEIN 2010). There is also preliminary evidence that some nanoparticles could have a negative impact on algae and plants, and impair the function or reproductive cycles of bacteria and fungi which play a key role in nutrient cycling that underpins ecosystem function (Navarro, et al. 2008).

Microorganisms are of great importance environmentally. They are the foundation of aquatic ecosystems and provide key environmental services ranging from primary productivity to nutrient cycling and waste decomposition (Klaine, et al. 2008). Yet the same antimicrobial properties of nanoparticles such as silver and titanium dioxide that make them useful for self-cleaning or germ-killing reasons could also interfere with beneficial bacteria in natural environments or waste treatment facilities (Klaine, et al. 2008). A preliminary study found that when small quantities of nano silver were added to activated sludge, the population of microbes and its activities declined, and four times the normal quantity of nitrous oxide was released (Knight 2010). This raises concerns not only regarding the potential for nano contaminants to disrupt the bacteria-driven waste processing of sewage treatment plants, but also regarding potentially vastly enhanced levels of greenhouse gas emissions from these plants.

Another recent study has demonstrated that nanoparticles of titanium dioxide inhibited the growth and nitrogen fixation activity of blue-green algae (Cherchi and Gu 2010). Blue-green algae are a type of bacteria that produce their own food via photosynthesis. Nano titanium dioxide induced both a dose and time dependent stress response. The study authors cautioned that the release of nano titanium dioxide in aquatic environments could potentially impact important biogeochemical processes, such as carbon and nitrogen cycling (Cherchi and Gu 2010). These cycles form the foundations of ecosystem function. This study is especially concerning in light of new studies that show that nano titanium dioxide is released into streams in effluent from sewage treatment plants (see below).

Nanomaterials may also pose ecological risks through their mobilisation of heavy metals or other pollutants in the environment. Nanomaterials may bind to organic chemical pollutants or transition metals, which may increase their toxicity (Moore 2006). Nanomaterials may also alter the transport and bioavailability of these pollutants (Navarro, et al. 2008), delivering them to sites within the environment or human body to which they would not normally have access (the Trojan horse effect). Nanomaterials have been shown to act as carriers of co-existing contaminants. A far higher bioaccumulation of cadmium in carps was found when nanoparticles of titanium dioxide were present (Zhang, et al. 2007). C60 fullerenes were found to alter the bioaccumulation and toxicity of two other environmental contaminants towards Daphnia magna, an aquatic invertebrate used by regulators as an indicator species; the toxicity of pentachlorophenol was decreased, while the toxicity of phenanthrene was increased (Baun, et al. 2008a). The toxicity and bioaccumulation of heavy metals in nano-form may become important environmental challenges (Bystrejewska-Piotrowska, Golimowski and Urban 2009).

There has been some suggestion that because many commercially used nanomaterials are soluble, or partially soluble, they pose no new risk of nanoparticle-mediated toxicity. That is, some have assumed that these nanoparticles rapidly dissolve into ions once released into waste water or aquatic systems. However, increasing numbers of studies have demonstrated that in nanoparticle form zinc oxide, silver, copper, cobalt oxide, manganese oxide, quantum dots and other soluble and partially soluble materials exert both ion and particle-mediated toxicity (Asharani, et al. 2008; Bai, et al. 2009; Brunner, et al. 2006; Griffitt, et al. 2009; King-Heiden, et al. 2009; Limbach, et al. 2007). Further, some studies have shown that these soluble or partially soluble nanoparticles accumulate in nanoparticle form in the organs, cells and cell nuclei of exposed animals (Asharani, et al. 2008; Griffitt, et al. 2009; Limbach, et al. 2007).

Because small quantities of potent nanomaterials can be used in place of much larger amounts of conventional materials, a common expectation has been that nanomaterials will lower energy and resource use and pollution. As is clear from the discussion above, the ecological cost of nanomaterials production processes is far greater than that associated with bulk materials. Moreover, irrespective of their being used in smaller quantities, the toxic burden of nanomaterials is predicted to be far greater than that of bulk materials by mass. In 2006 the Woodrow Wilson International Center for Scholars' Project on

Emerging Nanotechnologies predicted that 58,000 metric tons of nanoparticles will be produced world-wide from 2011 to 2020 (Maynard 2006). They estimated that given the potency of nanoparticles, this could have an ecological impact equivalent ranging from five million to a massive 50 billion tons of conventional materials.

> *"Claims that nanocomposites are 'environmentally safe,' 'environment(ally)-friendly' or 'eco-friendly' and that TiO_2 [titanium dioxide] nanoparticles are 'non-toxic' do not seem to have a firm foundation in empirical data."*

There is growing evidence that release of nanomaterials into the environment occurs even when they are embedded in composite materials. In nanocomposites containing organic polymers, there can be a substantial increase in degradability under solar or UV irradiation, as compared with non-nano polymers (Reijnders 2009; Som, et al. 2010). Thermal degradation may be enhanced by the incorporation of nanoparticles. Even when stability is important to nanocomposite design, nanoparticles may still be released. Reijnders concludes that given evidence that manufactured nanoparticles used in composites and coatings may be hazardous, "Claims that nanocomposites are 'environmentally safe,' 'environment(ally)-friendly' or 'eco-friendly' and that TiO^2 [titanium dioxide] nanoparticles are 'non-toxic' do not seem to have a firm foundation in empirical data" (Reijnders 2009, 874).

Exposure and nanoparticle transport modelling has predicted that up to 95 percent of nanoparticles used in cosmetics, coatings and cleaning agents and up to 50 percent of nanoparticles used in paints may end up in sewage treatment plants (Mueller and Nowack 2009). Waste and water treatment plants are not well equipped to remove nanoparticles before treated waste water (effluent) is discharged (Reijnders 2009). Kiser et al. (2009) have detected nanoparticles of titanium dioxide in sewage and biosolids. They found that titanium dioxide particles had an affinity for solids and the majority was removed in the treatment process. However, 10-100 micrograms per litre of titanium dioxide particles still remained in tertiary treated effluents which are released into streams and natural systems. Further, the authors warn that titanium dioxide concentrations in biosolids are likely to be much higher. Biosolids are then used as agricultural fertilisers, placed in landfills, incinerated, or dumped into oceans (Kiser, et al. 2009). Swiss researchers modelled the environmental concentrations of several commercially used nanomaterials and predicted that nano silver, titanium dioxide and zinc oxide released from sewage treatment effluents may already pose risks to aquatic organisms (Gottschalk, et al. 2009).

Some authors have suggested that nanoparticles will rapidly agglomerate or aggregate once released into the environment, thereby reducing the potential for them to exert nano-specific toxicity. However, agglomeration and aggregation processes, and disagglomeration and disaggregation processes are not well understood. Researchers at the University of California Center for Environmental Implications of Nanotechnology have demonstrated that bacteria can disagglomerate a common metal oxide (UC CEIN 2010). They note that this has implications for nanomaterial transport in porous media in the environment.

Importantly, there is preliminary evidence that agglomerates or aggregates of nanoparticles

Table 6: Life cycle assessment of nanoproducts compared to conventional products

Nanoproduct	Purpose of nano-component	Type of analysis, any constraints	Energy demands	Other environmental costs or benefits	Study authors
Nano titanium dioxide coated concrete pavement	The photocatalytic coating is designed to trap and absorb smog and air pollutants.	Hybrid life cycle assessment of nano TiO2 coated concrete pavement. Uses both LCA and Economic Input-Output modeling, with additional data added for energy requirements of nano titanium dioxide manufacture. Emissions data used are from the 2008 EIOLCA model developed by Carnegie Mellon which Khanna and Bakshi (2009) caution is based on coarse and aggregated data for a range of US industry sectors.	Not addressed.	Costs: Will increase global warming, fossil fuel depletion, water intake, ozone depletion, and impacts on human health. Benefits: will reduce acidification, eutrophication, air pollutants, and smog formation. Authors conclude that there is a net environmental benefit.	(Hassan 2010)
Carbon nanofiber (CNF) polymer composites	To enable production of strong, lightweight panels to replace steel panels in cars, thereby reducing car weight and increasing fuel efficiency.	Life cycle analysis comparing overall energy demands/ savings of CNF composite to steel. No account made of human health and environmental toxicity of CNFs, or end of life release of CNFs, primarily due to data gaps.	Depends on certain variables. CNF composites required 1.6-12 times the energy of steel to produce. Where CNFs are used at lower loadings, 1-4-10 percent savings in lifetime fuel (gasoline) use are predicted. These fuel savings offset the extra energy associated with CNF manufacture, delivering net energy savings. Where CNFs are used at higher loading (9-15 percent), their use may result in an overall increase of the fossil energy of the life cycle. Sources of uncertainty include: manufacturing efficiency of CNFs, the extent to which nanocomposites can practically replace existing steel panels, whether or not CNF composites offer the required functionality and aesthetics in use, and distance travelled by the car.	Not addressed. However, authors note that process LCAs (eg Khanna et al. 2008) have found CNF manufacture has a higher environmental burden compared to steel.	(Khanna and Bakshi 2009)
Clay nanocomposites	To enable production of strong, lightweight panels to replace steel or aluminum in cars, thereby reducing car weight and increasing fuel efficiency.	Life cycle analysis comparing overall energy and environmental demands/ savings of clay nanocomposites compared to steel. However, assessment does not use up-to-date data for nanomaterials production. Khanna and Bakshi (2009) have cautioned that the Economic Input-Output LCA (EIOLCA) model used in this study for information regarding energy and environmental impacts of nanocomposite production relies on coarse and aggregated data for different US industrial sectors. Specific process details are missing. Khanna et al. (2008a) note that due to omissions or approximations of data relating to the energy demands, release and impact of emissions of nanomanufacturing, the LCA accuracy is limited.	Life cycle energy savings are obtained by substitution of steel parts by nanocomposites in both 'lower bound' and 'upper bound' scenarios. The lower bound scenario would deliver less carbon dioxide emission reductions than would substitution of steel by aluminum (230kg per vehicle, compared to 310kg per vehicle), whereas the upper bound scenario would deliver more (414kg per vehicle).	The EIOLCA predicts that both upper and lower bound nanocomposite scenarios would deliver environmental savings in the areas of greenhouse gas emissions and toxic releases, with modest water savings. The lower bound scenario would result in greater generation of hazardous waste.	(Lloyd and Lave 2003)

Cont'd, Table 6: Life cycle assessment of nanoproducts compared to conventional products

Nanoproduct	Purpose of nano-component	Type of analysis, any constraints	Energy demands	Other environmental costs or benefits	Study authors
Platinum group metal (PGM) nanoparticles and nanofabrication for automotive catalysts	To use nanofabrication for better control of the shape, size and position of PGM particles in automotive catalysts. Aim to reduce PGM loading levels while maintaining performance, delivering resource and energy savings	Life cycle analysis comparing overall energy demands/ savings of reducing PGM use. However, assessment does not use up-to-date data for nanomaterials production or address any additional energy demands of nanofabrication. Khanna and Bakshi (2009) have cautioned that the Economic Input-Output LCA (EIOLCA) model used in this study relies on coarse and aggregated data for different US industrial sectors. Specific process details are missing. GaBi software is also used to calculate cradle to gate energy and environmental costs of noble metals. It is not clear that this is relevant to nanomaterials. Khanna et al. (2008a) note that due to omissions or approximations of data relating to the energy demands, release and impact of emissions of nanomanufacturing, the LCA accuracy is limited.	The authors do not assess the energy implications of nanofabrication of PGM catalysts. Nonetheless, they observe that reducing quantities of PGM required by the automotive sector will deliver energy savings: "If the benefits of also lowering vehicle emissions are retained, the nanotechnology would make a large life cycle environmental contribution".	Does not address environmental demands of nanofabrication. However, does state that PGM production requires large amounts of energy, water and ore and generates large quantities of tailings. Reduced PGM use will deliver savings in these areas.	(Lloyd, Lave and Matthews 2005)
Carbon nanofiber (CNF) reinforced windmill blades	To reinforce the interface of a glass fiber/ epoxy matrix. The aim is to enable production of lighter and more long-lived large windmill blades.	LCA of energy demands/ returns of CNF reinforced windmill blades, comparative to traditional material. No assessment of non-energy environmental or safety aspects.	Depends on certain variables, mainly manufacturing process, solvent handling and quantity of CNTs used. Cradle to gate processing of the CNF-windmill blades is 1.4 to 7.7 times more energy intensive than the original material. If CNF blades do result in both weight savings and increased life span, potential energy savings across the life cycle vary from insignificant to substantial. However, there may be practical constraints to using CNF hybrid materials; the authors note that "weight savings by CNFs may assume a prohibitively thin blade". The authors conclude that "it is not yet substantiated whether replacement of long carbon fibers is advantageous both mechanically and energetically".	Not addressed.	(Merugula, Khanna and Bakshi 2010)
Nano silver impregnated T-shirts	The antibacterial properties of silver may mean the T-shirts require less frequent washing, and at reduced temperatures.	LCA compared net energy savings of nano silver T-shirt compared to conventional polyester T-shirt under range of scenarios. Both flame spray pyrolysis and plasma/ sputtering nano silver manufacturing methods were compared. No assessment of non-energy environmental or safety aspects.	Depends on certain variables; in 2 of 3 scenarios nano silver use in T-shirts increased energy demands. Net energy savings are only achieved in the 'breakthrough' scenario where there is increased efficiency in nano silver manufacturing, comprehensive consumer uptake and behavioral change (reduced washing and at lower temperatures). The uncertainty in the assessment was relatively high.	Not addressed. Authors note that different nano silver production technologies have different environmental impacts. Further, nano silver released to the environment may negatively affect the function of sewage treatment plants.	(Frischknecht, Büsser and Krewitt 2009)

may still be toxic. Where toxicity is driven by the surface structure of a particle, the toxic properties of agglomerated or aggregated nanoparticles may be very similar to that of the primary nanoparticles that compose them. Bai et al. (2009) found that although in solution the nanoparticle zinc oxide they studied readily formed clusters of small and large aggregates, the (aggregated) nanoparticle zinc oxide exerted a greater toxic effect on developing zebrafish embryos than the corresponding concentration of zinc ions. Griffitt et al. (2009) also found that in solution nano silver and nano-copper readily formed suspensions that contained a substantial number of aggregates and agglomerates >100nm in size. Nonetheless, nano-copper was significantly more toxic to the exposed zebrafish than dissolved copper ions alone, and nano silver resulted in a dramatically higher silver gill content and silver body burden than dissolved silver ions alone. Chronic exposure of juvenile carp to sub-lethal doses of fullerene aggregates with average diameters of approximately 349 and/or 1,394 nm over a 32 day period caused significant oxidative stress, and reduced length and body weight (Zhu, et al. 2008).

Life cycle energy demands of nanoproducts compared to conventional products

It is important to conduct life cycle analysis on nanoproducts compared with conventional products, rather than simply assessing the energy demands of nanomaterials production, given that small quantities of nanomaterials may be used in a product.

The assumption is commonly made that because nanomaterials are used in such small quantities, their contribution to the energy demands of the products in which they are used will be negligible (Meyer, Curran and Gonzalez 2009). However, early nanoproduct comparisons have found that this is not the case. Carbon nanotube-reinforced polymer composites are also more energy intensive than conventional materials such as aluminium or steel that they may be designed to replace. A cradle to gate analysis found that for equal stiffness design, carbon nanofiber-reinforced polymer composites were 1.6 to 12 times more energy intensive than steel (Khanna and Bakshi 2009).

The product-use phase therefore governs whether or not any net energy savings can be realised for a given nanoproduct; the use-phase must be extremely efficient to justify the disproportionately large energy investment of manufacturing nanomaterials (Seager and Linkov 2009). Carbon nanocomposites may be extremely strong and light, but in applications such as civil infrastructure this will not result in use-phase energy savings (Khanna and Bakshi 2009). Where no energy savings can be anticipated via the use-phase of a nanoproduct, it is highly likely that the nanoproduct's life cycle energy demands will be more intensive compared to its conventional counterpart.

Not all nanoproducts that are specifically designed to save energy may offer net energy savings over their life cycle compared to conventional materials. Healy et al. (2008) observe that there are likely to be clear energy savings associated with the use of single walled carbon nanotubes (SWCNT) in microelectronics: a single SWCNT can form a switch that would require no power to maintain in the on or off position, yet would deliver significant energy savings through the use-phase of electronic devices. However, some nanoproducts that are designed to save energy such as lithium ion batteries or nanostructure-based solar cells may actually not offer net energy savings, or not be able to be produced en masse, because of problems associated with efficiency, materials purification, scaling up, use or cost constraints (Gupta et al. 2009; Seager et al. 2008).

Early life cycle analyses have shown that for a range of products, including nano silver T-shirts, carbon nanofiber-reinforced windmill blades and carbon nanotube polymer composites for cars, whether or not net energy savings or costs occur depends on a complex range of variables and assumptions (Frischknecht, et al. 2009; Khanna and Bakshi 2008; Merugula, et al. 2010). These LCAs have found that nanoproducts can impose net energy costs. These LCAs have been performed with inadequate understanding of nanomaterials performance in nanoproducts, realistic manufacturing processes and actual use conditions. Further, they exclude entirely consideration of the environmental and human health toxicities associated with the nanomaterials themselves, due to a lack of information. Nonetheless, they provide an interesting preliminary overview of the capacity for nanoproducts designed to achieve energy efficiency to deliver in this aspect (see Table 6).

Will efficiency gains result in environmental savings – or just expanded production?

Energy efficiency measures must form a key part of efforts to achieve dramatic and rapid cuts in greenhouse gas emissions. However, without tackling the economic growth model, and profligate patterns of production and consumption, any efficiency gains made possible by nanotechnology are likely to be absorbed by expanded production.

Uncertainty surrounds the net energy costs of nanoproducts designed to achieve energy savings. Early LCAs suggest that only those products that deliver substantial efficiency boosts in the product-use phase will recoup the huge energy investment of the nanomaterials manufacturing process. Most nanoproducts on the market offer no such potential, and so will come at a net energy cost. There is a common assumption – often implicit – that any efficiency gains achieved by nanotechnology will necessarily deliver environmental savings (Karn 2008). However, even where products do underpin efficiency breakthroughs, there is no guarantee that this will deliver real environmental savings, when set in a context of ongoing economic growth and no meaningful behavioural change. An analysis of US energy efficiency measures and their impact on energy consumption found that technical efficiency measures led to slightly higher energy consumption when not accompanied with lifestyle change (Adua 2010).

Environmental scientist and renewable energy advocate Mark Diesendorf advocates that pursuit of energy efficiency must form a central part of climate change mitigation measures; he observes that efficiency gains are the cheapest and fastest way to reduce our greenhouse gas emissions (Diesendorf 2009). Diesendorf warns that we should not let fear of the rebound effect stand in the way of pursuing energy efficiency. However, he suggests that 'packages' of household energy efficiency and renewable energy investment could be offered to consumers, such that energy savings are increased, the net cost of each package is zero, and so is the rebound. In this way, household economic savings achieved by energy efficiency could pay for most of the additional costs of cleaner energy supply [of course, this does not address industry, which is a majority user of electricity]. Diesendorf also backs proactive government policies to ensure that efficiency translates into environmental savings, rather than being consumed by greater growth. The evidence is compelling that without such measures, any nanotechnology-enabled efficiencies will be consumed through growth and increasing complexity of goods produced.

The New Economics Foundation (NEF) warns that throughout history, efficiency gains have simply underpinned expanded production and consumption (NEF 2010). Between 1980 and 2001, the Organization for Economic Cooperation and Development (OECD) countries experienced an average annual growth rate of 2.6 percent. In the same period, these countries' energy intensity declined 1.4 percent per year, partly due to energy efficiency measures, and partly due to the increasing shift of energy intensive industries to non-OECD countries (US EIA 2004). Nonetheless, energy consumption still rose 1.2 percent per year. That is, energy efficiency measures were able to assist in reducing the energy required per unit of economic output – and were therefore of environmental and economic value - but energy demand continued to grow.

Efficiency measures achieved by technological change frequently deliver smaller environmental or resource savings than was anticipated due to the 'rebound effect'. This refers to behavioural or systemic change in response to new efficiencies, which offset the gains of the new technology or other measures taken (Adua 2010). NEF cites the example of automobile efficiency to illustrate the rebound effect. Since 1975 fuel consumption has improved by only 5 percent in the Volkswagen Golf, despite huge improvements in engine efficiency. The failure of efficiency gains to translate into fuel consumption savings is related to a 50 percent increase in weight in the car over the same period, and a greater number of energy-demanding gadgets for entertainment and comfort (NEF 2010). That is, rather than achieving fuel savings, efficiencies have underpinned growth in the car weight and entertainment options.

The rebound effect has been observed in the semiconductor industry and in electronic goods more generally. Efficiency savings and lower production costs in this sector have driven expanded production, and more complex and more energy intensive products (Khanna, Bakshi and Lee 2008). Despite major reductions in energy consumption and ultrapure water use, chemical use per product and chemical waste generation have increased in semiconductor facilities due to greater wafer production and more complex processes (Sengul, Theis and Ghosh 2008). Electronic wafer cleaning, associated with high use of chemicals and surfactants, has increased fivefold in the past 25 years. Gutowski et al. (2009) surveyed 20 different manufacturing processes and found that the intensity of materials and energy used per unit of mass of material processed has increased by at least six orders of magnitude during the past several decades. That is, about one million times the energy per unit of mass of material produced is required in today's manufacturing processes. The researchers concluded that the increase of material and energy demands was primarily a consequence of the introduction of new manufacturing processes, driven by the desire for small-scale devices and more complex product features (Gutowski, Liow and Sekulic 2010).

Consumers are also vulnerable to the rebound effect; reduced production costs can mean reduced product costs, which can simply encourage greater consumption. The journal Environmental Science and Technology reports the European Commission environmental policy officer's personal opinion that "improving technology and boosting the efficiency of production has not reduced carbon emissions. Instead, as goods are produced more efficiently, they become cheaper, leaving consumers with more discretionary cash to buy more stuff" (Pelley 2009). Lending support to this view, Nielsen Wire reports that the number of televisions per United States household in 2009 was 43 percent higher than in 1990 (Nielsen Wire 2009). In 2010, the number of televisions per United States household was greater than the number of people per household (2.93 vs 2.5; Nielsen Wire 2010).

An editorial in *Nature Nanotechnology* (- 2007, 325) argued that "reducing demand, increasing efficiency and developing low-carbon forms of energy will all be necessary" to combat climate change. It observed, somewhat facetiously, that "there is not much nanotechnology can do to reduce demand – if people want to drive everywhere or watch 48-inch television screens science cannot stop them." However, the relationship between nanotechnology product commercialisation and consumer demand bears some scrutiny. Nanotechnology may be used to market products as 'green', therefore convincing consumers that further increases in their consumption may be offset by technology breakthroughs. Alternatively, nanotechnology may simply be used to market new generations of must-have clothing, cosmetics or electronic appliances, triggering new waves of consumption of ever more energy intensive products. For example Samsung is reported to be preparing to launch a carbon nanotube-television in 2011 (Wong 2010). The television's breakthrough point of marketability is improved image contrast and motion reproduction.

In this way, rather than delivering real environmental savings, carbon nanotube-reinforced lightweight planes could simply lead to bigger planes or more flights being taken, while imposing a new generation of health hazards and environmental costs. In addition to questioning the energy demands and toxicity of nanoparticle production, we need to question the logic that underpins the quest for economic growth at all costs and the rapacious appetite of wealthy consumers for ever more complex and small-scale prestige appliances that may be updated with increasing frequency. Without a change in the growth mentality, without industry restructuring and without changed consumer behaviour, there is little possibility any energy efficiency gains made by nanotechnology will deliver environmental benefits rather than simply driving greater economic expansion.

Rather than delivering real environmental savings, carbon nanotube-reinforced lightweight planes could simply lead to bigger planes or more flights being taken, while imposing a new generation of health hazards and environmental costs.

Further, should energy savings be achieved by nanomanufacturing or production systems, we should be wary of pursuing energy efficiency at the expense of significant non-energy environmental costs. Early evidence of the significant quantities of potentially toxic waste generated by nanomaterial production and the ecotoxic behaviour of many nanoparticles themselves demand that the environmental burden of nanoproducts be scrutinised rigorously alongside their life cycle energy demands. Often when a technological or manufacturing process is supposedly improved, the problems or environmental costs are shifted to another area of the life cycle. We should employ life cycle analysis to help prevent this type of oversight (Grubb and Bakshi 2008).

Is 'green nano' a greenwash?

Nanotechnology is often promoted as a cleaner, greener, superior alternative to existing manufacturing and technologies. The title of the 2002 Australian Government report "Smaller, cleaner, cheaper, faster, smarter" is emblematic of this tendency (Commonwealth Department of Industry, Tourism & Resources 2002). The field of green nano is used to demonstrate nanotechnology's environmental credentials. Green nano has two ostensible goals: producing nanomaterials without harming the environment or human health, and producing nanoproducts that provide solutions to environmental challenges (Karn 2008). A third and less openly acknowledged goal of promoting green nano is promoting public acceptance of the emerging industry: "Actively engaging in the development of green nano can play a significant role in reassuring the public and maintaining the power and potential of nanotechnology to realise benefits for society, the economy and the environment" (Eckelman, Zimmerman and Anastas 2008, 320).

Some researchers have predicted that because such large sums of money are being spent by governments on nanotechnology research and development, funding priorities will be targeted to deliver societal benefit (Lloyd and Lave 2003). Unfortunately such predictions are not reflected in the funding figures to date. The Woodrow Wilson Center's Project on Emerging Nanotechnologies conducted a detailed analysis of the 2006 US National Nanotechnology Initiative (NNI) budget request and found that only 1 percent of US$1.06 billion - $11 million - was allocated to research that was highly relevant to addressing nanotechnology risks (Maynard 2006). Maynard noted that this was in contrast to the $38.5 million figure cited by the NNI, "rais[ing] doubts about the validity and the basis of the NNI figures" (Maynard 2006, 18). In 2009, from a total of US$1.7 billion, the NNI states that $76 million was spent on environment, health and safety research (NSTC 2010). This figure is still only 4.47 percent of the total budget, and it is not clear how much of this work is highly relevant to risk research. For comparison, in the same year 26.78 percent ($459 million) was spent on nanotechnology research by the Department of Defense.

Beyond risk research, despite the public relations focus on socially and environmentally responsible green nano, the field attracted a mere 0.02 percent of the United States National Nanotechnology Initiative research funding from 2000-2004 (Dunphy Guzman, Taylor and Banfield 2006); as of 2007 it continued to attract a very small proportion of US government research funding (Eckelman, Zimmerman and Anastas 2008). As Allenby and Rejeski (2008, p268) observe: "Despite early calls for a life cycle approach to nanotechnology development, proactive management of emerging risks, and the greening of production infrastructure, little has happened as the normal wheels of technological progress grind forward."

In addition to the very low research funding, and commercial and political priority attached to the field of green nano, the huge uncertainties surrounding nanomaterials' behaviour in environmental systems are a major obstacle to scientists' capacity to achieve the much-touted "safety by design." Nora Savage of the United States EPA cautions that no one knows yet what nanomaterials will do in the presence of other chemicals, or if they might heighten other chemicals' risks: "I know people are trying to design environmentally benign nanomaterials… but all toxicity tests to date show that behaviours change with agglomeration, as coatings degrade, [and so on]. As they end up in the water, it's going to be much more complex" (Lubick 2009, 1249). The uncertainty about potentially substantially increased toxicity of nanomaterials such as cadmium core quantum dots should coatings degrade has been emphasised by researchers (Bouldin, et al. 2008; Chen, et al. 2008b; King-Heiden, et al. 2009).

Industry has been extremely reluctant to voluntarily provide information to governments about the commercial use of nanomaterials, let alone what is known of nanomaterial risks. The United Kingdom's two year voluntary reporting scheme resulted in only 12 submissions (Breggin, et al. 2009), despite the UK Department of Trade and Industry estimating that there were then 372 organisations involved in micro- and nanomanufacturing in the UK (Berger 2007b). Only 29 companies and trade associations participated in the US EPA's "Basic Program" as part of the Nanoscale Materials Stewardship Program (NMSP); another seven companies committed to submit information at a future date. In its interim report on the NMSP, the US EPA estimated that "approximately 90% of the different nanoscale materials that are likely to be commercially available were not reported" (US EPA 2009,

Companies are not conducting risk assessments on nanomaterials they use, or taking steps to protect workers from unsafe exposure

There is disturbing evidence that a majority of companies using manufactured nanomaterials are not conducting basic risk assessments, or providing relevant risk information regarding the nano-ingredients in the products they sell, let alone taking proactive measures to reduce the toxicity of the nanomaterials they sell, or to limit the broader environmental costs of nanoproduction.

A survey of Swiss and German companies that work with nanomaterials found that of those companies who elected to respond, 65 percent did not ever perform any risk assessment on their nanomaterials (Helland, et al. 2008).

A survey commissioned by the Australian government of Material Safety Data Sheets (MSDS) provided by suppliers in relation to nanomaterials found that over 84 percent did not provide nano-relevant risk information (Safe Work Australia 2010). Despite serious safety concerns about the potential for some forms of carbon nanotubes to cause asbestos-like pathogenicity, 11 of the 12 MSDS that related to carbon nanotubes compared their potential risk to graphite.

An international survey of companies and institutions involved in nanotechnology research, development and commercialisation found commissioned by the US-based International Council On Nanotechnology found similar results (UCSB 2006). Reported practices in the handling of nanomaterials, with some exceptions, were based on criteria unrelated to any perceived risks stemming specifically from working with nano-scale materials.

The international survey also found that companies were not routinely alerting their customers to the need for safety measures regarding disposal of nanowaste: "When asked, organizations generally recommended disposal of nanoproducts as hazardous waste, though they did not frequently report conveying this information to their customers" (UCSB 2006, 7).

27). Further undermining the usefulness of the scheme, a number of the submissions EPA did receive did not contain exposure or hazard-related data. The EPA also noted that the low rate of engagement – seven companies - in its 'In-Depth Program' "suggests that most companies are not inclined to voluntarily test their nanoscale materials" (US EPA 2009, 27).I

In an article that explores the industrial ecology of emerging technologies, Allenby and Rejeski quote Princeton historian Ed Tenner's observation of the "tendency of advanced technologies to promote self-deception." They note that "the chance of such self-deception increases exponentially in the case of so-called 'national prestige technologies', such as nanotech" (Allenby and Rejeski 2008, 268). They warn that: "In our view, it is all too likely that industrial ecology may have missed the off-ramp to a green nanotech future about 5 years ago". They caution that the United States and other governments keen to cash in on nanotechnology's economic promise are largely avoiding attempts to steer nanotechnology development into greener channels.

> ***"In our view, it is all too likely that industrial ecology may have missed the off-ramp to a green nanotech future about five years ago."***
>
> - Allenby and Rejeski 2008

In a study commissioned by the European Parliament, Fiedeler questioned the common assumption that nanotechnology holds the potential to provide a substantial contribution to the solution of various ecological problems, including high consumption of energy and materials and the generation of waste (Fiedeler 2008). In a review of current examples and concepts of nanoproducts and applications, Fiedeler concluded that because nanomaterials themselves may introduce new toxicity risks, and because the nanomaterials production process may itself involve the production and use of hazardous materials, "it is unclear whether the current use of NT [nanotechnology] really provides new opportunities for the avoidance of hazardous substances" (Fiedeler 2008, 314).

Arguably, given the concerns about both nanomaterials and nanomaterial production processes, a first step in the green nano hierarchy would be to avoid or eliminate use of nano until its environmental implications are better understood and its safety is demonstrated. In his review, Fiedeler cautioned that each nano-application should be assessed in detail on a case by case basis. "Because such an assessment is complex and time consuming, proposals for substitution [of hazardous substances with nanomaterials] should only be analyzed if the benefit would be outstanding or if no existing solution is already available" (Fiedeler 2008, 313). In short, Fiedeler proposed that before we even ask of a nanoproduct "will it achieve what it is claimed to achieve," that we first ask: "do we need this nanoproduct" and "do alternatives to this nanoproduct exist?" Similarly, other researchers have suggested that at the product design stage, the question should be asked whether there are any alternatives to use instead of manufactured nanomaterials that achieve the same functionality (Som, et al. 2010). Unfortunately, in the rush to market new cosmetics, electronic goods, sports equipment and clothing, this is not a question many companies are prepared to ask.

In the view of Friends of the Earth, the illusion of green nanotechnology is just that – an illusion that is promoted by a range of nanotechnology proponents keen to practice self-deception. Green nano does not currently exist in any meaningful sense – as an area of research, as industry practice, or as a viable alternative to the status quo. Yes, the environmental burden of nanomaterials manufacture could certainly be reduced, but neither researchers nor industry will know enough in the near future to design environmentally benign nanomaterials or methods for their manufacture. In the meantime, the inconvenient truth is that nanomaterials manufacturing is a dirty, energy and water intensive process that both uses and produces many toxic chemicals, while nanomaterials themselves pose serious and poorly understood health and environmental risks.

regulatory gaps

The need to adopt the precautionary principle to manage the serious but uncertain risks associated with nanotechnology has been recognised explicitly by governments from five continents. At the 2008 International Forum on Chemical Safety in Dakar, 71 governments, 12 international organisations and 39 NGOs recommended "applying the precautionary principle as one of the general principles of [nanotechnology] risk management" (IFCS 2008).

Swiss Re, one of the world's largest reinsurance agents, has also called explicitly for application of the precautionary principle in management of nanotechnology risks. In its detailed report into nanotechnology, the reinsurance agent warns: "In view of the dangers to society that could arise out of the development of nanotechnology, and given the uncertainty currently prevailing in scientific circles, the precautionary principle should be applied whatever the difficulties" (Swiss Re 2004, 47).

The United Kingdom's Royal Society, the world's oldest scientific institution, recommended in 2004 that given the evidence of serious nanotoxicity risks, nanoparticles should be treated as new chemicals and subject to new safety assessments before being allowed in consumer products. It also recommended that nano-ingredients in products should be labelled, to give people the chance to make an informed choice. Further, the Royal Society recommended that factories and research laboratories should treat nanomaterials as if they were hazardous, and that releases of nanomaterials to the environment should be avoided as far as possible until it could be demonstrated that the benefits outweighed the risks (UK RS/RAE 2004). The European Union's Scientific Committee on Emerging and Newly Identified Health Risks also recognised the many systemic failures of existing regulatory systems to manage the risks associated with nanotoxicity (EU SCENIHR 2006).

Unfortunately, in most countries the overwhelming majority of nanomaterials remain effectively unregulated. Regulatory systems in the United States, Europe, Australia, Japan and other countries treat all particles the same; that is, they do not recognise that nanoparticles of familiar substances may have novel properties and novel risks (Bowman and Hodge 2006; Bowman and Hodge 2007). Although many nanomaterials now in commercial use pose greater toxicity risks than the same materials in larger particle form, if a substance has been approved in bulk form, it remains legal to sell it in nano form. There is no requirement for: new safety testing; product labelling to inform consumers, workers or employers; or new occupational exposure standards or mitigation measures to protect workers or to ensure environmental safety. Incredibly, there is not even a requirement that the manufacturer notify the body that regulates its products that they are using nanomaterials.

The most significant efforts to close the legal gaps in nanotechnology regulation have been made in Europe. Europe has already amended its cosmetics directive to require nano-specific notification and assessment of most nanomaterials used in sunscreens and cosmetics (European Commission 2009). This is anticipated to take effect in 2012 or 2013. More pertinently to this report's focus, following a proposal from its environment committee, the European Parliament has committed to a review of all European regulation to investigate its ability to cope with the new challenges and risks of nanotechnology (Euractiv.com 2009). The European Commission is set to complete its regulatory review of nanomaterials by the end of 2011. It will focus specifically on the inclusion of nanomaterials under the REACH regulation on chemicals, and the results will be included in the 2012 REACH review.

The European Parliament's environment committee has proposed measures under its Restriction of Hazardous Substances (RoHS)

Directive for a ban on nano silver and on long, multi-walled carbon nanotubes (European Parliament Press Service 2010). The Committee also called for other electrical and electronic material containing nanomaterials to be labelled. The proposed measures now face (considerable) debate. The Wuppertal Institute, a German sustainability research centre, has also argued for the extension of the RoHS Directive to cover photovoltaics (Saurat and Ritthof 2010). This would require an end to the use of toxic heavy metals such as cadmium in the new generation of nano solar panels.

In Australia, in late 2009 the National Industrial Chemicals Notification and Assessment Scheme proposed for consultation new measures that would seek to close the legal loopholes surrounding nanomaterials used in industrial chemicals and cosmetics (NICNAS n.d.). However, these proposals remain at consultation stage. The federal government has explicitly rejected calls for a mandatory register of manufactured nanomaterials in commercial use (Lauder 2010) or new regulations to protect workers from occupational exposure (Hall 2009).

In the United States, both the Environmental Protection Agency (EPA) and the Food and Drug Administration (FDA) have recognised the current gaps in the regulation and oversight of nanomaterials, but their actions thus far have been wholly inadequate. The EPA has continued to delay regulation for nanomaterials despite legal action brought forward by a coalition of consumer rights organisations, led by the International Center for Technology Assessment (ICTA) and including Friends of the Earth (Kimbrell 2008). The Agency has opened many comment periods with regard to nanosilver technologies and their appropriate regulation, though these have yet to produce significant regulatory changes. The FDA has followed a similar path of 'all talk no action'. Manufacturers are able to bring to market nanoproducts in many sectors without any premarket assessment, testing, data or approval by FDA.

The United Nations University concluded that the potential risks of nanotechnologies are an obstacle to the widespread rollout of nanoproducts to address climate change: "One of the major obstacles highlighted is the lack of a robust transparent regulatory regime able to address concerns that have been expressed by some about potential human health and other environmental risks associated with some forms of this technology" (Esteban, et al. 2008). Friends of the Earth recognises that without credible, transparent and precaution based regulation, the entire nanotechnology sector faces an uncertain and high risk future.

Preventing the dumping of hazardous nanowaste on to poor communities and countries is of the utmost importance. Strict, mandatory regulation is required to ensure extended producer responsibility by companies for the nanoproducts they manufacture. It must be the responsibility of companies to take back products where they are faulty or otherwise at end of life, to recycle wherever possible, and to pay for responsible disposal of other components. International effort is also required to prevent the export of nanowaste from Northern to Southern countries. This should include efforts to strengthen the Basel Convention, an international treaty that controls transboundary movement of hazardous waste and its disposal. It is not acceptable that as a leading proponent of nanotechnology and technological development, the United States has so far refused to sign this treaty. Further, it is essential that stricter measures are introduced to prevent the dumping of used electronic equipment under the guise of export.

There is an urgent need for regulation to require the design of nanoproducts that may be more readily recycled. If we are to prevent imminent shortages of rare metals used in electronics and energy applications, the United Nations Environment Programme has warned that taking measures to promote recycling of high tech products is essential (UNEP 2010a).

Finally, beyond the important issue of managing nanomaterial risks, this report provides clear evidence for the need to ensure that energy and greenhouse gas emissions analysis is conducted as part of the regulatory process. The widespread use of nano silver in frivolous consumer products such as odour-eating socks may pose a serious risk of accelerating release of nitrous oxide from bacteria (see above). This is a compelling reason to halt the sales of such products.

technology assessment and accountability is required at the international level

Beyond policy making at the national level, intergovernmental bodies must urgently address regulatory gaps surrounding nanotechnology and begin to assess the environmental and socio-economic impacts of new technologies, as well as create ways to encourage meaningful public participation in decision making.

Climate related nanotechnologies could potentially gain access to global markets and receive widespread government support through market based mechanisms, such as the Clean Development Mechanism (CDM) of the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol (UNFCCC n.d.).

'Technology transfer' from Northern to Southern countries is one of the four key topics being discussed as part of the UNFCCC international negotiations that work to solve the climate crisis. The other topics are mitigation, adaptation and financing (ETC Group 2009). Decisions about technology transfer are now in the hands of the UNFCCC Expert Group on Technology Transfer. This group seeks to pair venture capital with projects in the developing world—all too often focused towards generating profit.

While the CDM was set up to help cap greenhouse gases (GHGs) in order to combat dangerous climate change, it has also become an opportunity for venture capitalists to gain large amounts of funding and support for questionable projects. Under the guise of technology transfer, the CDM opens all doors for new climate technologies to gain traction and financial support. This makes it critical to stop bad technologies from getting approved through this mechanism. Through the CDM, nanotechnologies could quickly be adopted and imposed on developing nations despite the fact that they are untested and unproven for safety and efficacy. Other high risk and unproven technologies, such as geo-engineering and biochar have already been the subject of intense lobbying and advocacy at the UNFCCC.

One of the roles of the CDM is to distribute certified emission reduction (CER) credits (equivalent to one ton of carbon dioxide) to developed nations that can be traded and sold, allowing developed nations to meet Kyoto emission reductions without a direct reduction of emissions. Developed nations can submit a project for approval by the CDM Executive Board (CDM EB) to work bi-laterally with a developing country. All that is required to back up the proposal is a claim that the project would contribute to sustainable development in the developing country. Carbon trading is surrounded by speculation and is a questionable method for fending off climate change (Lohmann 2006). Many projects approved by the CDM are biomass projects, which encourage land grabbing and undermine biodiversity.

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Civil society groups (including Friends of the Earth) have taken action at the UNFCCC, highlighting the need to discard unhelpful and dangerous technologies while supporting those that have the potential to help (ETC Group 2009). A civil society declaration was prepared for the UNFCCC climate negotiations that took place last year in Copenhagen. The declaration stated the following:

> *Precaution demands the careful assessment of technologies before, not after, governments and inter-governmental bodies start funding their development and aiding their deployment around the globe. There is already a precedent in international law: the Cartagena Protocol on Biosafety, ratified by 157 countries, gives effect to this principle on genetically modified organisms. National and international programs of public consultation, with the participation of the people who are directly affected, are critical. People must have the ability to decide which technologies they want, and to reject technologies that are neither environmentally sound nor socially equitable.*
>
> *We therefore demand that a clear and consistent approach be followed internationally for all new technologies on climate change: States at COP 15 [Conference of Parties 15] must ensure that strict precautionary mechanisms for technology assessment are enacted and are made legally binding, so that the risks and likely impacts, and appropriateness, of these new technologies, can be properly and democratically evaluated before they are rolled out. Any new body dealing with technology assessment and transfer must have equitable gender and regional representation, in addition to facilitating the full consultation and participation of peasants, indigenous peoples and potentially affected local communities.*
>
> *Read the full declaration at http://www.etcgroup.org/en/node/4956.*

Another intergovernmental body highly influential in technology adoption is the International Energy Agency (IEA). One of the main goals of the IEA is to ensure "energy technology collaboration" between countries. Despite this, the agency's members include only wealthy nations, with a total lack of representation by the Global South (IEA 2010). It is therefore likely that the IEA operates in wealthy countries' interests.

The Delegation of Bolivia to the United Nations Framework Convention on Climate Change has explicitly denounced the promotion of elite, high risk technologies under the guise of addressing climate change. "[Bolivia] rejects the practices and technologies harmful to humankind and the environment, including agrochemicals, corporate-controlled seeds and intensive water use, genetic engineering, particularly genetic use restriction technology, biofuels, nanotechnology, and geo-engineering" (UNFCCC Delegation of Bolivia 2010).

equity and access: concerns that nano will widen the gaps

Nanotechnology proponents have emphasised its utility for poorer communities and Southern (less industrialised) countries. However, its development trajectory suggests that applications and solutions that are demonstrated to have value in mitigating climate change may be inaccessible to poor communities. In a field in which aggressive patenting has begun, Northern (industrialised) countries dominate. Further, the corporate and national interests of Northern countries appear to be shaping nanotechnology's development and deployment. There are concerns that nanotechnology product manufacture and waste disposal will be located in poorer communities and countries, exacerbating existing environmental injustice. At a broader level, nanotechnology's expansion may deepen existing inequities at a time when Southern countries are facing the brunt of climate change.

Climate change raises some of the sharpest equity dilemmas: the world's poorest people are most vulnerable to the adverse consequences of greenhouse gas emissions that they are the least responsible for. The United States' Department of Energy states that in 2001, per capita consumption of fossil fuels in OECD countries was 450 percent higher than in non-OECD countries. The G-7 highly industrialised countries (United States, Japan, Germany, Britain, France, Canada and Italy) consumed even more fossil fuels per person than the rest of the OECD (US EIA 2004). The huge climate debt owed by Northern countries has been emphasised at international forums, including the Cochabamba Peoples' Conference in Bolivia.

High profile nanotechnology proponents such as the late Richard E. Smalley have argued that breakthroughs in nanotechnology for energy will be of most benefit to poor people (The James A. Baker III Institute for Public Policy 2005). An international survey of nanotechnology experts also predicted that nanotechnology applications in energy production, conversion and storage would be the biggest contribution the sector could make to helping achieve the (anti-poverty) Millennium Development Goals (Salamanca-Buentello, et al. 2005). By boosting poorer countries' access to more reliable and more sustainable forms of energy, the hope is that nanotechnology will offer Southern countries new opportunities for economic growth and development, while minimising the environmental cost.

However, this optimistic view has been challenged by senior scientists. The United Kingdom's Royal Society observed that nanotechnology breakthroughs—as with previous technical breakthroughs—may be inaccessible to poor or marginalised groups (UK RS/RAE 2004). In many instances, it is the accessibility of a technology

or service that requires improvement, not simply technical capacity. Efficient and relatively cheap technologies already exist to address energy, public health, sanitation, medical, and agricultural needs of poor people, yet these are often not accessible to those who have most need of them (Invernizzi, Foladori and Maclurcan 2008).

Intellectual property and patents are dominated by wealthy countries

Nanotechnology may concentrate ownership and control of essential platform techniques, processes, and products (ETC Group 2005). Should predictions of nanotechnology's potential as a platform technology prove accurate, countries and companies that are making early investments, patenting aggressively, and can afford to defend patent claims, are likely to cement and expand their control of key industries and trade – including in energy applications. Companies that are investing heavily in nanotechnology applications such as energy that have a long lead time from lab to product are eager to make a financial return. It is unlikely that such companies will make their technology freely available to poor communities. US company Nanosolar has been described as "notoriously secretive" about its nano solar technology. The Guardian observes that Nanosolar "is quite open about wanting to restrict access to the technology to give it a market advantage" (Vidal 2007).

In 2007 the Kingdom of Saudi Arabia observed that the number of producers of nanomaterials had already decreased as consolidation had increased, and that multi-national chemical companies now dominate the market (Kingdom of Saudi Arabia 2007). Addressing questions of nanotechnology ownership and access will be critical if climate change applications can be made to work (Fauset 2008).Corporate Watch emphasises that it is important to question who owns technology hardware (power stations, pipelines), as well as who controls patents and other intellectual property. They caution that technologies such as nano solar are likely to be dominated by a few companies owning fundamental patents and charging royalties for their use. Corporate Watch point out that over four thousand patents on 'clean technologies' had been granted in 2006 in the USA alone. It is conceivable that possible solutions to climate change could be held to ransom.

Beyond the potential for corporations or institutions to control key products or applications in the energy sector, nanotechnology could potentially increase the patenting of key research tools or even particular nanocompounds. Bowman notes that: "Of particular concern is the progressive blurring of the invention/discovery interface under Article 27 [of the Agreement on Trade-Related Aspects of Intellectual Property Rights (TRIPS Agreement)] that may produce uncertainty over the types of nanoproducts that can be patented… wide interpretation of Article 27(1) may result in the monopolization of fundamental molecules and compounds" (Bowman 2007, 313). Strong protection of scientific and technological intellectual property, including the patenting of research tools, can also constrain the capacity of scientists in Southern countries to carry out their own research and development (Forero-Pineda 2006). Without active international cooperation, Southern countries must exert considerable energy to access scientific results and information.

In an analysis of nanotechnology patent grants up to 2003, Northern countries were well ahead of Southern countries in registering nano patents; the United States was the most active nation in the world for registering patents, followed by Japan, Germany, the United Kingdom and France (Hullman 2006). There is a wide disparity among Southern countries in nanotechnology investment, development and patenting. In recent years patent grants have grown in high growth emerging economies (Liu and Zhang 2007). In particular, the patent growth rate in China has been remarkable; since 2005 China has held the largest number of nanotechnology patents internationally (Preschitschek and Bresser 2010). Nonetheless, the majority of patents worldwide are still held by Northern countries, and the majority of Southern countries hold few nanotechnology patents. Patenting trends therefore reflect not only a North-South but also a South-South divide.

Nanotechnology is being driven by the interests of wealthy countries

Beyond questions of ownership and accessibility, some observers have suggested that nanotechnology development is driven by Northern interests and does not reflect a prioritisation of poor people's needs. Northern countries not only dominate in overall nanotechnology publications, but also have the highest impact publications. The country with the highest impact nanotechnology publications is the United States, followed by European countries then Japan (Kingdom of Saudi Arabia 2007). European countries have the greatest degree of international collaboration in nanotechnology published research. The dominance by Northern countries of high impact nanotechnology research can mean that the interests of Northern governments, industry and consumers shape the development trajectory. "Since nanotechnology's development is essentially guided by corporations' search for profits, a majority of innovations are directed to Northern, affluent societies" (Invernizzi, Foladori and Maclurcan 2008, 136).

Private sector investment in techno-scientific research is traditionally oriented towards delivering products for potential customers with wealth and access, rather than the needs of the poor and disenfranchised (Woodhouse and Sarewitz 2007). But even in public research institutions and universities, there is strong pressure on scientists to produce commercially useful research and to pursue intellectual copyright. Jamison (2009) argues that the links between researchers and industry have become so intimate that science has entered a new, market oriented mode of knowledge-making, where profitability is central. He suggests that this diminishes the possibility that nanotechnology will be developed for altruistic or public interest purposes, and results in wilful neglect of its social, cultural, and environmental implications.

There is ongoing debate about the role of technology in causing or deepening inequality on a global scale. Many observers suggest that technology deepens existing inequality,

Carbon nanotubes have diminished crop yields, increased crop uptake of pollutants in experimental studies

Carbon nanotubes are one of the nanomaterials most commonly mooted for use in energy and climate applications. Yet a preliminary study has found that two types of carbon nanomaterials - C70 fullerenes and multi walled nanotubes (MWNT) - delayed rice flowering by at least 1 month (Lin, et al. 2009). They also reduced significantly the yield of exposed rice plants (fullerenes reduced seed set by 4.6%, MWNT by 10.5%). Seeds exposed for only 2 weeks to fullerenes passed these onto the next generation of seeds.

A separate study found that exposure to carbon nanotubes made wheat plants more vulnerable to uptake of pollutants (Wild and Jones 2009). Carbon nanotubes pierced the cell wall of wheat plants' roots, providing a 'pipe' through which pollutants were transported into living cells.

These studies raise concerns about the potential for waste from nanomaterial or nanoproducts manufacturing facilities or disposal sites to contaminate farmland. Carbon nanomaterials could reduce yields of one of the world's most important staple crops and leave another more vulnerable to pollutant uptake.

even where it is not the main force creating it; Woodhouse and Sarewitz (2007) caution that new techno-scientific capacities introduced into a non-egalitarian society tend to benefit disproportionately already privileged people. Others point to the complex dynamics of inequality and suggest that in some contexts emerging technologies could reduce rather than increase inequalities (Cozzens, Gatchair and Thankur 2006).

Despite ongoing disagreement about technology's role in deepening inequity, our experience in recent decades demonstrates conclusively that technological innovation alone will not redress inequity. During the last 30 years, a period of significant technological progress and innovation in which microelectronics, information technologies, medical treatments, and telecommunications were developed, the gap between the global rich and the global poor has widened. When global inequality has increased during the expansion of such powerful technologies over recent decades, the obvious question is "why would it be any different for nanotechnologies?" (Invernizzi, Foladori and Maclurcan 2008).

Nanotechnology appears likely to exacerbate existing environmental injustices, such as the exposure of poorer communities to toxic substances and wastes in their workplaces or neighbourhoods. Southern countries may find themselves shouldering a disproportionate amount of risk by becoming manufacturing centres for nanoproducts that Northern workers would prefer not to handle.

Nanotechnology may exacerbate existing environmental injustice

Nanotechnology appears likely to exacerbate existing environmental injustices, such as the exposure of poorer communities to toxic substances and wastes in their workplaces or neighbourhoods. Southern countries may find themselves shouldering a disproportionate amount of risk by becoming manufacturing centres for nanoproducts that Northern workers would prefer not to handle. Since Southern countries usually have weaker environmental regulations, it is possible that international companies will choose to locate manufacturing plants in these countries, exposing local communities to greater risks (Invernizzi, Foladori and Maclurcan 2008). Governments in Southern countries have generally been reluctant to introduce strong environmental policies and regulations for fear of driving out high tech industry (Tu and Lee 2010). Electronics manufacturing sites in Taiwan, China, Thailand, Mexico and the Philippines have been associated with toxic contamination of neighbouring environments and farmlands, while lax regulations have left pollution unmonitored and unmanaged (Tu and Lee 2010).

Southern countries and poor communities may also be targets for nanowaste disposal by Northern countries and companies. Southern countries have historically borne the brunt of waste products: "In a globalised world, it has been shown that many waste products end up in developing countries, or countries of transition, where the disposal or recycling is not well organised and thus products may end up in landfills or even on unpoliced dumping sites throughout the area" (Som, et al. 2010, 166). The United Nations Environment Programme warned years ago of a "mountain" of hazardous electronic waste ('e-waste') being dumped by the Global North in the Global South (BBC 2006). Despite a European ban on the exporting of defunct electronic goods, large-scale trafficking continues. The United States, which has not ratified the Basel Convention which controls export of hazardous waste, is estimated to export up to 80 percent of its defunct electronic goods (Lewis 2010). Africa and South Asia are common destinations. Workers at unpoliced, makeshift recycling plants face routine unsafe exposure, while burning e-waste is common.

beyond nanotechnologies: alternative action for the energy and climate change crises

In many ways nanotechnology offers the ultimate attempted techno-fix to problems that require integrated social, economic and political solutions. We are concerned that rather than providing real solutions to our most pressing problems, nanotechnologies will underpin a new wave of industrial expansion that will magnify existing resource and energy use and exacerbate environmental destruction.

A 2008 Corporate Watch report on the subject of techno-fixes highlights the need for governments and society to “get realistic.” The report suggests that “technologies are a useful part of the solution, but techno-fixation isn’t. Other changes are even more important than technology, and equally technically possible. Whether or not they are achieved depends on the actions we take now” (Fauset 2008).

Friends of the Earth suggests that rather than putting all our faith – and public funding - into nanotechnology, hoping that it will deliver “drop-in” substitute solutions that prolong the status quo, we should undertake actions to avoid dangerous climate change by pursuing substantive reform at a number of levels:

Reduce energy demand

Industry observers have predicted that world energy demand is likely to be 1000 EJ/yr by 2050 - about double what it is now (Trainer 2010). An Exajoule (EJ) is equal to 1018 joules. ‘

Simple living’ advocate Ted Trainer emphasises that there are strong environmental reasons to back a swift transition to renewable energy and that ongoing reliance on fossil fuels is impossible because of its effect on greenhouse gas emissions. Nonetheless, he concludes that because of efficiency, intermittency and variability constraints, and financial costs, renewable energy cannot support the demands of an energy intensive consumer society, especially one committed to ongoing economic growth (Trainer 2010).

Senior Research Fellow Felice Frankel and Harvard University Professor George M. Whitesides also emphasise the need to question the limits of renewable energy to meet growing energy demand. In their book about the nanoscale they observe that “solar electricity is a good idea, but not a good enough idea to save us from ourselves. Either we have to find more energy elsewhere, or use less” (Frankel and Whitesides 2009). These authors provide an important reality check. We cannot rely on technologies to solve our climate and environment issues, while committing to ongoing patterns of economic growth and burgeoning energy intensity; fundamental structural change of economic and production systems is required.

Renounce over consumption

Spiralling patterns of profligate consumption and waste are unsustainable – irrespective of any potential for technology-driven efficiencies of production. As Professor Stevels, from the Dutch Design for Sustainability Lab at Delft University of Technology, warned the journal *Environmental Science and Technology*, technological fixes alone will not achieve much needed reductions in carbon dioxide emissions and pollution. Professor Stevels says that reducing consumption is essential and advises policy makers to: "Be courageous, tell your citizens the unpleasant and inconvenient truth—do not suggest that technology alone will be good enough" (Pelley 2009).

The need to dramatically reduce consumption, especially in wealthy countries, is a key point made by Trainer (2008; Trainer 2010). Trainer recognises that there is an historical and unjust gap between the environmental impacts of rich and poor and because of this debt, Southern countries are entitled to a proportionately greater share of the world's resources. However, he observes that if by 2070 there are nine-plus billion people on the planet and all of them have the "living standards" Australians are predicted to have by then, assuming 3 percent annual growth from now, total world economic output would need to be 60 times greater than it is now. "If by that point in time we have reduced present environmental impacts by 50 percent, we would have made a Factor 120 reduction in the rate of impact per unit of economic output or consumption [that is, reduced the environmental impact per unit of economic output by 120 times]… This is far beyond the realm of credibility" (Trainer 2008).

Transition to a steady state economy

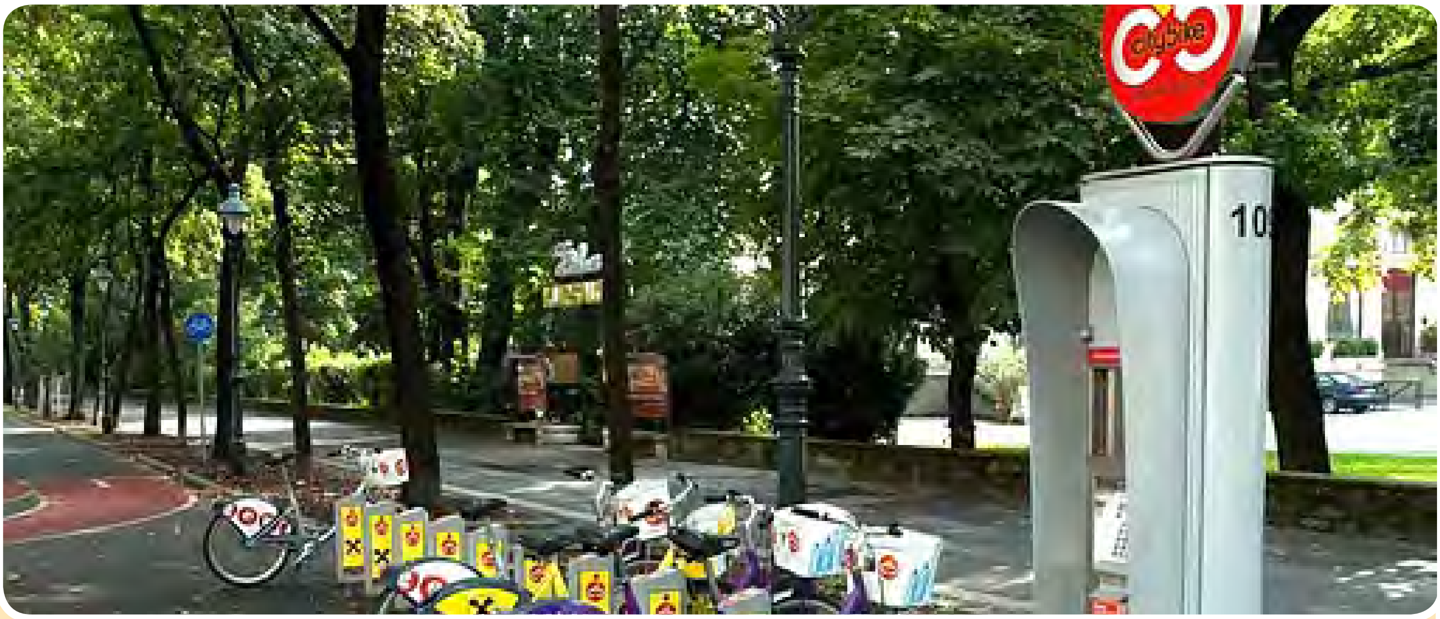
The idea that governments and industries in wealthy countries should seek a 'steady state' economic pathway, rather than one based on unbounded economic growth was once unthinkable. However, this has been the key proposal from the UK's Sustainable Development Commission's (SDC) "Redefining Prosperity" project and its "Prosperity without growth" report (Jackson 2009). The report, authored by the SDC's Economics Commissioner Professor Tim Jackson, emphasises that the profits and benefits of growth have been distributed in a massively inequitable manner. It recognises that for poorer countries, higher income levels and greater material prosperity can deliver important health, educational and social outcomes. However, it argues that people in wealthy countries can lead more fulfilling lives and increase their "social prosperity" without further economic growth. This is an important idea whose time has truly come.

Encouraging a dependence on unproven nanotechnologies and other techno-fixes will jeopardise our ability to successfully confront the climate change crisis.

The President of the United States and many of his predecessors have attempted to green corporate actions and interests. In President Barack Obama's 2010 Earth Day statement, he mixed the need to safeguard our planet with the country's financial interests: "We have…renewed our commitment to passing comprehensive energy and climate legislation that will safeguard our planet, spur innovation and allow us to compete and win in the 21st century economy" (White House 2010). Averting dangerous climate change requires us to challenge this core aim to "compete and win in the 21st century economy." Unless governments and industry abandon their commitment to endless economic expansion, no amount of efficiency measures will ever enable us to live sustainably on a finite planet.

Support renewable energy solutions

Viable renewable energy technologies exist now to meet a large proportion of our energy needs. This has been the key premise of reports such as Beyond Zero Emission's "Zero Carbon Australia Stationary Energy Plan" (Beyond Zero Emissions 2010). This report argues that it is technically feasible and affordable to shift Australia's entire fossil fuel energy use to existing solar and wind energy technologies in the next ten years. The report has received high level backing and endorsement, including from the International Energy Agency and the President of the Australian Academy of Technological Sciences and Engineering. Trainer has questioned assumptions made in the report regarding the likelihood that Australia's levels of 2008 energy demand can be substantially reduced, while



allowing for ongoing economic growth. He also questions assumptions regarding the capacity of renewables to overcome intermittency problems (Trainer 2010a). Nonetheless, even if these criticisms are founded, the report's findings make clear that a significant proportion of Australia's energy needs could be met using existing renewable energy technologies, within the next 10 years, given the political will for action.

In their review of the capacity of silicon photovoltaics to replace fossil fuel energy at a global scale, New Zealand researchers have concluded that from a materials and technology viewpoint, with better storage solutions and some acceptance of partially intermittent supply, renewable energy sources including silicon photovoltaic technologies, wind energy and large-scale hydro could replace the current 2010 electricity supply system. However, they caution that further economic growth will run up against material constraints: "unless a steady state economic system is soon put in place, overshoot is inevitable" (Lloyd and Forest 2010). They conclude that further use of fossil fuels should be to strategically assist a transition to a renewables-based and less energy intensive economy, rather than in simply trying to "prop up" the world economy and business as usual (Lloyd and Forest 2010).

Invest in mass transport and non-motorised transport systems

While there is much discussion in the media and from politicians about actions that individuals can take to reduce their climate impact, there is less recognition of the need for infrastructure investment to support large-scale behavioural change. The transportation sector is one of the most energy intensive and is responsible for a significant proportion of greenhouse gas emissions. Infrastructure investment and policies to get freight off roads and onto rail would help reduce the emissions associated with industrial transport. Investing to ensure the availability of safe, sustainable, affordable transport systems for personal transport is essential to diminish reliance on inefficient private vehicle transport. Investment in high speed rail networks between major cities that provide viable alternatives to short haul flights is essential.

Integrated, multi-modal public transport systems, combined with support for walking and cycling, could reduce urban congestion associated with daily commuting, improve people's enjoyment of urban spaces, make a positive contribution to public health, and make a key contribution to reducing greenhouse gas emissions associated with private transport. Financial measures such as congestion taxes, when coupled with support for more affordable and accessible public transport, can also assist.

Support for non-motorised options is essential, especially in communities that are not already reliant on private vehicle transport. Communities working with UK NGO Practical Action have created climate friendly transportation projects employing novel bicycle designs, animal power, and other non-motorised modes of transportation. These allow communities to function without motorised vehicles or large highway infrastructures that are oriented towards the wealthy who can afford cars (Practical Action n.d.). To complement these projects, earth roads have also been built as alternatives to highways. For example, earth roads made of low-tech in situ materials have been built in Sri Lanka, which are able to withstand torrential rain.

Smarter urban design and town planning

Also at the level of collective planning, urban design can play a vital role in shaping less car dependent, less energy intensive and more liveable communities and cities. Urban design plays a role in the density of housing, the size of houses proportional to land, proximity to major transport centres and employment opportunities, the availability of green space and agricultural land, the orientation of streets and buildings, the efficiency requirements of building and street tree planting.

Sustainable, re-localised agriculture

Friends of the Earth backs calls from La Via Campesina and others for stronger measures to support small scale farmers, and to maintain and redevelop local food markets. This offers strong social benefits, including improved resilience against fluctuating world food prices and employment opportunities for regional and rural communities. Re-localising agriculture also offers strong environmental benefits, including reduced greenhouse gas emissions associated with transporting food around the world.

Further, we advocate for greater government support for agro-ecological and organic agriculture. Organic agriculture could help reduce small farmers' capital costs and reliance on agribusiness companies. Agro-ecological initiatives in Brazil have delivered yield increases of up to 50 percent, improved incomes for farmers, restored local agricultural biodiversity and reinvigorated local rural economies (Hisano and Altoé 2002). A 22-year trial in the United States found that organic farms produced comparable yields, but required 30 percent less fossil fuel energy and water inputs than conventional farms, resulted in higher soil organic matter and nitrogen levels, higher biodiversity, greater drought resilience and reduced soil erosion (Pimental, et al. 2005).

International agreement on targets to reduce emissions, explicitly recognising Northern countries' climate debt

The World People's Conference on Climate Change and the Rights of Mother Earth held in Cochabamba, Bolivia was attended by more than 35,000 participants from 150 countries around the world - ranging from environmental justice groups to indigenous rights organisations to governmental representatives, United Nations officials, and heads of state. The People's Agreement, a declaration set forth during the conference, called for governments of developed countries to fulfil their first round reductions and obligations established by the Kyoto Protocol. Further, The People's Agreement called for them to adopt during the second period, which lasts until 2017, more radical commitments of greenhouse gas emission reductions. The People's Agreement called for reductions of at least 50 percent within their territories, based on 1990 levels, so that the increase in global temperature does not exceed 1° C.

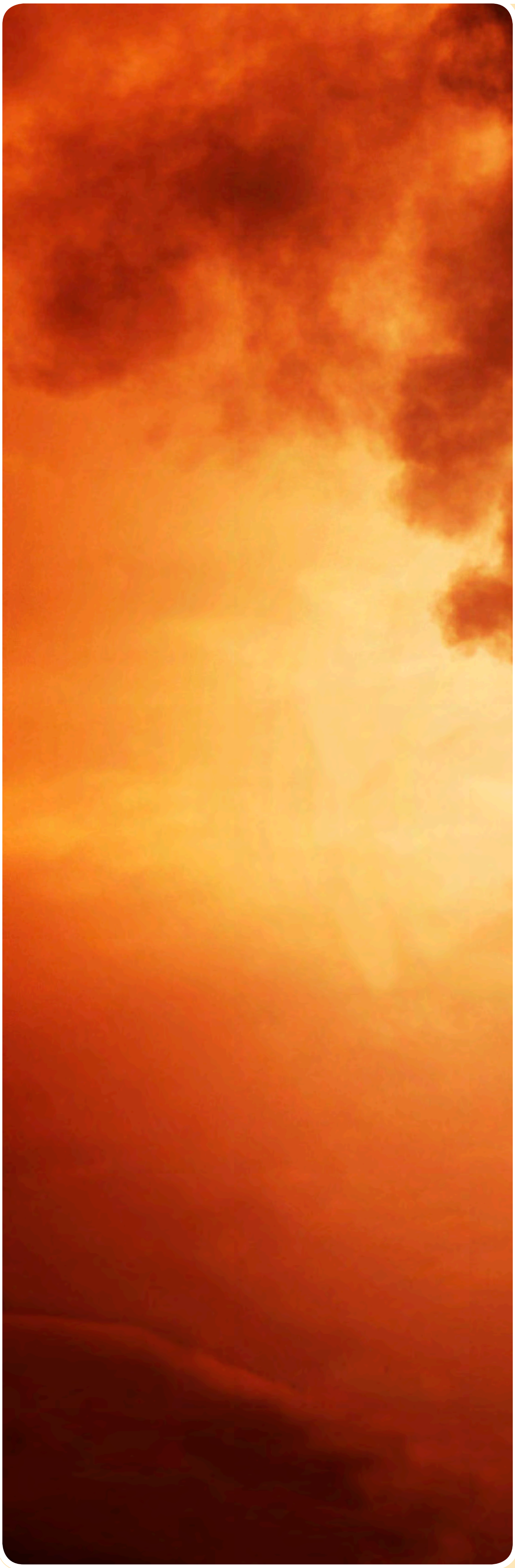
the nano climate and energy 'revolution': a nano step forward, several steps back?

When it come to climate change, the nanotechnology industry has over-promised and under-delivered. The energy demands of making nanomaterials are unexpectedly high. Many nanomaterials used in these applications have been shown to pose toxicity problems. The difficulties in bringing products to market have been underestimated. In addition, many nano applications rely on rare metals whose supply is limited.

Perhaps of most concern, nanotechnologies are being developed by the world's biggest petrochemical companies to identify new oil and gas reserves and to increase extraction. Public funds are also being invested for this purpose in countries around the world including Australia (CSIRO n.d. a), the United Kingdom (UK EPSRC n.d.), the United States (U.S. DOE, n.d.; Karoub, 2004), Mexico (IEA 2009), Japan (Endo, et al. 2008) and Saudi Arabia (Kingdom of Saudi Arabia 2007). At a time when we need to end our reliance on fossil fuels, we must ensure that public funding is not funnelled into this type of research.

Friends of the Earth recognises that some nanotechnologies will offer useful opportunities to improve renewable energy technologies. For example, nanomaterials used in supercapacitors have the ability to dramatically increase the energy that can be stored from wind power. However, our investigation reveals that many of the products designed to save energy will in fact result in greater emissions and energy demands over the product life cycle. This is because of the high energy demands of nanomanufacturing and of recycling nanoproducts. The potential for nanowaste to interrupt carbon and nitrogen cycling is a serious concern.

Valuable public funding should be directed at areas that have the most capacity to deliver near term reductions in greenhouse gas emissions. Companies and industries sectors should be required to demonstrate how their research, development or products has the potential to contribute to greenhouse gas emissions reductions – and how they have taken the energy demands of nanomaterials manufacture into account. This will not necessarily, or often, be nanotechnology applications. Some areas of nanotechnology research are a dangerous distraction from the real emissions mitigation we need to be undertaking – and represent a substantial opportunity cost for mitigation measures that could instead be receiving public funding. The hydrogen sector is one highly funded area of nanotechnology research that we conclude has no real capacity to contribute solutions to the climate change crisis.



It is important to recognise that the number of nanoproducts on the market that offer no potential for energy savings greatly outnumber the applications that do. The nanoproducts that dominate current sales and product inventories, such as cosmetics and personal care products, are not only energy intensive to manufacture, but offer no potential for energy savings through their use. This is true of many – if not most – nanoproducts on the market. "As is typical of rapidly growing industries, nanotechnology manufacturers are more focused on maximizing production and technological development than on environmental efficiency or sustainability" (Seager and Linkov 2009, 426).

Some areas of nanotechnology research are a dangerous distraction from the real emissions mitigation we need to be undertaking – and represent a substantial opportunity cost for mitigation measures that could instead be receiving public funding.

Friends of the Earth argues that high tech 'drop-in' techno-fixes will not be enough to save us from climate change; we need system level change. Encouraging a dependence on unproven nanotechnologies and other techno-fixes will jeopardise our ability to successfully confront the climate change crisis. In many instances the cheapest and most effective energy savings will be achieved through demand reduction and policy to support it.

friends of the earth recommendations

During the past five years, Friends of the Earth has called for a moratorium on the commercialisation of nanoproducts until nanotechnology-specific regulation is introduced to protect the public, workers and the environment from their risks and until the public is involved in decision making. The United Kingdom's Royal Society and Royal Academy of Engineering has similarly called for a prohibition on the intentional release of nanomaterials into the environment until the benefits can be demonstrated to outweigh the risks (UK RS/RAE 2004). However, despite a growing body of toxicological evidence, few steps have been taken to address these urgent concerns.

A precautionary approach to nanotechnology is essential for all classes of nanoproducts. Without government action a whole new generation of more energy intensive nanoproducts will flood the market; we need regulations to evaluate not only safety but energy and greenhouse gas (GHG) implications of nanotechnologies. Specifically we need regulation to:

- Safeguard people and the environment from nanotoxicity risks, including those of antimicrobial products
- Evaluate the energy demands and GHG emissions associated with nano product manufacture
- Ensure producers' responsibility for end of life product recovery and recycling
- Require manufacturer take-back and recycling programs; support product design to maximise recyclability
- Require labeling to support people's right to know
- Establish comprehensive and precautionary legislation to manage the risks associated with nanotechnology in general
- Ban export of dangerous nanowaste and defunct nanoproducts, especially to the Global South

A precautionary approach to nanotechnology is essential for all classes of nanoproducts. Without government action a whole new generation of more energy intensive nanoproducts will flood the market; we need regulations to evaluate not only safety but energy and greenhouse gas implications of nanotechnologies.

All nanomaterials must be subject to new safety assessments as new substances, even where the properties of larger scale counterparts are well known. All manufactured nanomaterials

must also be subject to nano-specific health and environmental impact assessment and must be demonstrated to be safe prior to approval for commercial use. The assessments of nanomaterials must be based on the precautionary principle and the onus must be on manufacturers to comprehensively demonstrate the safety of their product. No data, no market. All relevant data related to safety assessments, and the methodologies used to obtain them, must be placed in the public domain. Friends of the Earth also calls for greater prioritisation of research into life cycle analysis and energy demands of nanomanufacturing, and clear criteria for decision making about priorities for publicly funded research. Rigorous assessment of nanoproducts would require complex, time consuming, and expensive detailed scientific analysis. This should only be undertaken for technologies with the utmost of potential and where a simpler substitution is not available.

Suggestions for workers and the public

Workers need protection from the risks of occupational exposure to nanomaterials. This is particularly important given the evidence that some forms of carbon nanotubes behave like asbestos and can cause mesothelioma. It would be unforgivable to let nanotechnology repeat the asbestos tragedy. Occupational health is important everywhere, but especially in the Global South where workers have already faced unsafe workplace and environmental exposure from the electronics sector. This requires strong, precaution based regulation to prevent the use of nanomaterials whose safety has not been demonstrated. Governments must also enact strong 'right to know' legislation, requiring industry disclosure of nanomaterials handling to all affected workers. Workers should talk with their colleagues or union representatives about opportunities for collective action to secure a safe work place. The public needs the freedom to choose nano-free products through clear and mandatory labeling. Many people will want to avoid nanoproducts not only because of toxicity risks, but also as a means to reduce their carbon footprint. People should also explore opportunities for collective action to ensure that the health of people and the environment is not jeopardised by nanotechnology. Holding governments to account for their prioritisation of public funding is essential. Public funding for research and development should be directed to areas that offer immediate opportunities for greenhouse gas emissions cuts, rather than propping up petrochemical exploration and extraction.

Glossary

Antioxidant

A molecule which slows or prevents destructive oxidation (the interaction of substances with oxygen in a process that can lead to their breakdown). Oxidative stress can damage cells.

Biocide

A biocide is a pesticide used in non-agricultural applications, mainly as an anti-microbial agent.

Biopolymer

Any polymer (a long repeating chain of atoms) found in nature. Examples include starch, proteins and DNA.

Bioavailability

Bioavailability measures the extent to which a substance can reach the systemic blood circulation and its availability at the site of action.

Carbon fullerene ('buckyball')

A fullerene is a pure carbon molecule composed of at least 60 atoms of carbon which has a shape similar to a hollow soccer ball or a geodesic dome.

Carbon nanofibers

Feature a 'stacked cup' fiber configuration. Have diameter varying between 70 and 200 nm and a length of 50 to 100 μm.

Dendrimer

Dendrimers are three-dimensional, synthetic macromolecules with branching parts, usually formed using a fabrication process at the nanoscale.

Granuloma

A small mass or nodule of chronically inflamed tissue that is usually associated with an infective process or injured tissue, for example as seen in Crohn's disease, tuberculosis, sarcoidosis etc.

In vitro

Experiment performed in a test tube or culture.

In vivo

Experiment performed in a living organism.

Nanocomposite

Materials that are created by mixing nanomaterial fillers into a base material, for example plastic polymers.

Nano-sensor

Nanoscale chemical, biological or physical sensory points or system used to detect and convey information about a given environment, eg temperature, pH, location, or the presence of diseased tissue.

Nanotubes

A nanomaterial which resembles a cylinder. Often made of carbon, but also titanium dioxide, boron and other elements. Single walled carbon nanotubes (SWCNT) are composed of a single cylinder of carbon atoms, while multi walled carbon nanotubes (MWCNT) comprise multiple concentric cylinders of carbon atoms. Nanotubes are very strong and light and excellent conductors of electricity.

Nanowires

A nanowire is an extremely thin wire with a diameter on the order of a few nanometers (nm) or less.

Biopersistent

Materials that our bodies are not able to decompose into substances which can be used or excreted.

Oxidative stress

An imbalance between the production of reactive oxygen and a biological system's ability to readily detoxify the reactive intermediates or easily repair the resulting damage.

Polymer

A substance made of many repeating chemical units or molecules. The term polymer is often used in connection with plastic, rubber, or elastomer.

Quantum dots

Quantum dots are nanoscale spheres of inorganic materials that show novel optical properties, enabling light from different wavelengths to produce visible light.

Reactive oxygen species (ROS)

Very small molecules which are highly reactive due to the presence of unpaired valence shell electrons, includes oxygen ions, free radicals and peroxides. ROS form as a natural byproduct of the normal metabolism of oxygen and have important roles in cell signaling. However, during times of environmental stress ROS levels can increase dramatically and result in significant damage to cell structures (oxidative stress).

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In this report, Friends of the Earth puts the 'green' claims of the nanotechnology industry under the microscope. Our investigation reveals that the industry has over-promised and under-delivered. Many of the claims made regarding nanotechnology's environmental performance are not matched by reality. Worse, the energy and environmental costs of the nanotechnology industry are far higher than expected.

Carbon nanotubes are touted as one of the most promising nanomaterials for energy savings applications. Yet they may be one of the most energy intensive materials known to humankind. Researchers calculate that the embodied energy in a single kilogram of carbon nanotubes may be as great as 167 barrels of oil. A woman's weight in nanotubes would embody the same energy as the atomic bomb that exploded over Hiroshima (63 terajoules).

"Very few people have looked beyond the shiny promise of nanotechnology to try and understand how this far-reaching new technique is actually developing. This report is an excellent glimpse inside, and it offers a judicious and balanced account of a subject we need very much to be thinking about."

- Bill McKibben, author, environmentalist, founder 350.org

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