OAKDENE HOLLINS

Environmentally Beneficial Nanotechnologies

Barriers and Opportunities

A report for the Department for Environment, Food and Rural Affairs

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1 Executive Summary

The purpose of this Defra commissioned study is to provide an overview of the areas where nanotechnology could have a beneficial environmental impact above current technology and the barriers preventing its adoption. Green House Gas (GHG) reduction was taken as the major factor in targeting environmentally beneficial nanotechnologies. Five nanotechnological applications were subject to detailed investigation: fuel additives, solar cells, the hydrogen economy, batteries and insulation.

Summary of nanotechnologies

1) Fuel additives: Nanoparticle additives have been shown to increase the fuel efficiency of diesel engines by approximately 5% which could result in a maximum saving[a] of 2-3 millions of tonnes (Mte) per annum of CO_2 in the UK. This could be implemented immediately across the UK diesel powered fleet. However this must be tempered by concerns about the health impact of free nanoparticles in diesel exhaust gases. *Recommendations include: Comprehensive toxicological testing and subsidised independent performance tests to validate environmental benefit.*

2) Solar cells: The high prices of solar cells are inhibiting their installation into distributed power generation, preventing increased energy generation from renewables. Nanotechnology may deliver more benefits in significantly decreasing the cost of production of solar cells. Conservatively, if a distributed solar generation grid met 1% of our electricity demand, approximately 1.5 Mte per annum of CO_2 could be saved. The major barrier to this technology is the incorporation of the nanotechnology into the solar cell, not the nanotechnology itself. The UK is one of the world leaders in understanding the fundamental physics of solar cells, but we lack the skills that allow us to transfer our science base into workable prototypes. *Recommendations include: Develop programmes and facilities for taking fundamental research through to early stage prototypes where established mechanisms can be employed to commercialise new technologies. Develop centre of excellence in photovoltaics (either from existing centres or completely new) which allows cross fertilisation of ideas from different scientific disciplines.*

[a] It should be noted that the CO_2 savings quoted throughout this summary are for guidance and represent the absolute maximum saving achieved through full adoption of the technology, it is unlikely that these figures will be met using nanotechnology and should be taken as an order of magnitude to compare relative benefits of the nanotechnologies.

3) The hydrogen economy: Hydrogen powered vehicles could eliminate all noxious emissions from road transport, which would improve public health. If the hydrogen were generated via renewable means or using carbon capture and storage, all CO_2 emissions from transport could be eliminated (132 Mte per annum). Using current methods of hydrogen generation, significant savings in carbon dioxide (79 Mte per annum) can be made. The hydrogen economy is estimated to be 40 years away from potential universal deployment. Nanotechnology is central to developing efficient hydrogen storage (which is likely to be the largest barrier to wide scale use). Nanotechnology is also a lead candidate in improving the efficiency of the fuel cells and in developing a method for renewable hydrogen production. Although we do not have, in global terms, a substantial automotive R&D base, the international nature of these companies will allow ready integration of UK innovation into transport. *Recommendations include: Consider the use of public procurement to fund hydrogen powered urban public transport to create a market and infrastructure for hydrogen powered transport. Continue to fund large demonstration projects and continue R&D support.*

4) Batteries and supercapacitors: Recent advances in battery technology have made the range and power of electric vehicles more practical. Issues still surround the charge time. Nanotechnology may provide a remedy to this problem by allowing electric vehicles to be recharged in much more quickly. If low carbon electricity generation techniques are used, CO_2 from private transport could be eliminated (resulting in a maximum potential saving of 64 Mte per annum) or, using the current energy mix, maximum savings of 42 Mte per annum of carbon dioxide could be made. Without nanotechnology, electric vehicles are likely to remain a niche market due to the issues of charge time. Significant infrastructural investment will be required to develop recharging stations throughout the UK. *Recommendations include: Fiscal incentives to purchasers such as the congestion charge scheme, fast track schemes for commercialisation and cultivation of links with automotive multinationals.*

5) Insulation. Cavity and loft insulation are cheap and effective, however, there are no easy methods for insulating solid walled buildings, which currently make up approximately one third of the UK's housing stock. Nanotechnology may provide a solution which, if an effective insulation could be found with similar properties to standard cavity insulation, could result in emission reductions equivalent to a maxim potential of 3 Mte per year. Ultra thin films on windows to reduce heat loss already exist on the market. There are claims that nano-enabled windows are up to twice as efficient as required by current building standards. However, industry believes that significant further insulative savings in glass maybe made instead using aerogels, which themselves are nanostructures. *Recommendations include: Fund a DTI Technology Programme call on novel* *insulation material for solid walled buildings and include in government estate procurement specifications highly insulating nanotechnology based windows.*

Nanotechnology is likely to have a significant positive effect on the UK's green house gas emissions. Initially, these effects are likely to be the result of large numbers of small innovations. An R&D infrastructure that allows the development of good science into a commercial product is important. Public procurement and policy can be used (with caution) to act as a market pull for environmentally beneficial nanotechnologies. From the areas we have studied, nanotechnology could reduce our green house gas emissions by up to 2 % in the near term and up to 20 % by 2050 with a similar saving being realised in air pollution. These savings are based on the wide scale adoption of nanotechnology and the assumption that predicted breakthroughs within the field will occur when expected. Some of the findings and recommendations made within this report echo those made in the Stern report in 2006.

Figure 1: Summary of environmentally beneficial nanotechnologies

Application	Impact of nanotech in area [1]	Infra-structural changes [2]	Benefit (Mte CO_2 per annum) [3]	Timescale for implementation (yrs) [4]
Fuel efficiency	Critical	Low	<3	<5
Insulation	Moderate	Low	<3	3-8
Photovoltaics	High	Moderate	c.6	>5
Electricity storage	High	High	10-42	10-40
Hydrogen Economy	Critical	Very high	29-120	20-40

1 Impact of nanotechnology describes the effect nanotechnology is likely to have in the area compared to other technologies.
2 Infrastructural changes indicates the effort bring the nanotechnology to market.
3 Benefit is the estimate of the maximum potential CO_2 saving by implementing the technology.
4 Timescale for implementation is the projected distance (in years) before the technology will be fully implemented.

2 Introduction

2.1 Purpose of the report

Nanotechnology is the study and manipulation of materials at the nanometre scale. One nanometre is one billionth of a metre and is the width of approximately ten atoms. The fact that at this scale materials exhibit different properties to larger bulk materials is being exploited by researchers to develop new products with new functionalities. There is wide ranging speculation on the potential uses of nanotechnology in areas from cosmetics through to solar cells. This report has been commissioned to determine the potential environmental benefits that could be achieved by using nanotechnology. The goal of the study is to identify environmentally beneficial nanotechnologies (EBNTs), determine the barriers preventing their adoption and (where appropriate) make policy level recommendations to encourage the implementation of these technologies. Although the report deals with innovation and environmental technologies, it does not attempt to deal comprehensively with policy responses, which have been ably assessed in previous UK studies.[a] This report will focus on the potential positive aspects of nanotechnologies and compare the advantages of these with alternatives. Where possible, the added value of using nanotechnology over conventional technologies will be described.

Nanotechnology can be described as a 'platform' technology. Used on its own, the environmental benefits of nanotechnology are likely to be modest. Most nanotechnologies will need to be incorporated into a larger system or product or may require end user behavioural changes in order to be implemented. The barriers to adoption of these technologies may be system changes rather than specific technology changes, therefore the barriers are likely to include system and social issues as well as technological and development issues.

[a] For example "innovation and environmental challenges: policy options for the UK", Imperial college Fabian, 2001.

2.2 Approach

The information and data contained within this report has been sourced from primary and secondary literature and interviews with relevant experts. The report structure can be sectionalised into:

- **An initial survey of nanotechnology** identifying those technologies which have the potential to deliver environmental benefit. The study is focussed from end user demands rather than individual technologies. For example an environmentally important challenge such as reducing green house gases (GHGs) through improvements in engine efficiency will contain a suite of nanotechnologies with different approaches and functions. By grouping the technology in this way it is easier to compare the advantages of the nanotechnologies with alternative technologies. This approach also contextualises the nanotechnologies, resulting in the scope of the technology widening to include issues surrounding adoption which do not relate to technological or research centred barriers.
- **Ranking the nanotechnologies**: The survey highlighted a number of different technology areas where nanotechnology could provide some environmental benefit. These were then ranked, where possible, on their potential environmental benefit over and above current or competing technologies. Most of the technologies identified are still in the experimental or development stage, therefore a measure of the likelihood of the success of the technology was also included. This is designed to assess the potential impacts of the nanotechnologies. There will undoubtedly be some error within this assessment though, due to the experimental and unpredictable nature of research and development and the non-linear functioning of the innovation process. It is also likely that nanotechnologies will appear in environmental applications outside those currently forecast. However it is a 'best efforts' exercise to bring some objectivity to the potential environmental benefits that can be provided by nanotechnology.
- **In depth study on the barriers of EBNT**: Based on the above ranking, a selection of the technologies which have large environmental benefits and are likely to reach the market was made. This selection was then subject to further research to determine barriers, route to market, policy implications, solutions and recommendations. These studies also estimate the potential GHG savings achievable by complete adoption of the technology. It should be noted that these are 'order of magnitude' calculations and that accurate calculations are beyond the scope of this report.
- **Policy recommendations**: Based on the research, policy level recommendations were made, where appropriate, to encourage the implementation of EBNTs. Comparisons with other national programmes for nanotechnology were also drawn.

2.3 Defra's environmental challenges

Within the context of this study it is important to outline Defra's key environmental challenges.[a] This forms the basis of the market pull for this report. The following describes the areas most relevant to this work:

- **Energy:** The current UK's energy mix is heavily reliant on fossil fuels. This ultimately leads to the UK emitting nearly 600 million tonnes of CO_2 annually, which is linked to climate change and also issues over security of supply. This challenge covers both the reduction in energy use, either through technological advancement or behavioural change, and the use of 'low carbon' technologies to decouple energy production from carbon dioxide emissions.
- **Water:** The continual growth in housing stock in the south east of England is putting increased pressure on this region's limited water resources. There is a need to find a low cost, low energy solution to the UK's regional water vulnerability.
- **Waste:** Addressing the rising levels of waste generated in the UK is one of the most visible environmental challenges. Reducing waste either during production or through reuse or recycling is an important goal.
- **Food and Farming:** Farming has shaped the UK's landscape. Industrialisation of farming in the UK has improved food output but has had negative environmental impacts on, for example, biodiversity. New methods must be developed which reduce the impact of modern farming on the environment whilst maintaining yields.
- **Land:** The high population density in the UK puts pressure on available land. Developing remediation technologies for contaminated land will reduce pressure on the UK's green space.

[a] For example see "Open minute between David Miliband and the Prime Minister, June 2006"

2.4 Environmental and human health risks

There are well publicised concerns surrounding the toxicological impacts of nanomaterials on human and environmental health. It is beyond the scope of this study to discuss these issues in depth and the reader is directed towards extensive literature on the subject.[a,b,c] It is clear that there is a need for further research into the toxicological hazards posed by nanotechnology, however, the risks associated with nanotechnology are not only due to the hazard but also to exposure.[d] The manufacture and end of life treatment of nanomaterials could potentially lead to a high risk of exposure across all nanotechnologies, but such exposure can be minimised through the introduction of best working practices. However during the use phase of these materials there is the potential for exposure to the user or wider environment which varies according to application. A nanomaterial which is contained or packaged within another material, such as plastic or glass, does though present less of an exposure issue than a free nanoparticle. Where possible the report will draw attention to the potential exposure of the general public to these materials.

[a] Nanoscience and nanotechnologies: opportunities and uncertainties, The Royal Society & The Royal Academy of Engineering, 2004.
[b] Nanotechnology: Small Matter, Many Unknowns, Swiss Reinsurance company, 2004.
[c] http://www.hazards.org/nanotech/safety.htm
[d] P. T. Anastas; J. C. Warner *Green Chemistry: Theory and Practice*; Oxford University Press: Oxford, 1998.

3 Significant environmentally important nanotechnologies

In order to identify the most promising environmentally beneficial nanotechnologies, a survey of the current state of the art in nanotechnology, combined with forecasted estimates of the potential environmental impact of their main applications, was conducted. Nanotechnology is likely to be part of an overall package to deliver an environmental benefit. Therefore the focus has been on environmental needs and how nanotechnology can address those needs. This approach has led to the identification of several different nanotechnological approaches for each area.

3.1 Summary of areas

A more detailed analysis of the individual technologies can be found in Appendix 1. The policies which have been implemented to develop EBNT are outlined in Appendix 3. From this initial work, it is clear that nanotechnology could have a significant effect on a diverse range of applications. In some of the near market products the effects of nanotechnology are simply to increase the surface area of the material, which results in higher activity. More advanced applications use the properties at the nanoscale to produce new materials with unique properties. Fifteen applications in three areas were identified where nanotechnology could be important for the environment:

3.1.1 Energy generation and storage

These technologies are concerned with new methods for the generation and storage of energy (primarily electricity). The technologies are being developed to reduce the UK's dependence on fossil fuels and consequently begin the process of decoupling carbon dioxide emissions from energy. In addition, these technologies are likely to have a positive impact in reducing the concentrations of NOx and SOx in the atmosphere by reducing the quantity of fossil fuels used in the generation of electricity. The nanotechnologies which may help reduce the carbon impact of generating energy are:

- **Electricity storage:** Nanotechnology may enable improved efficiency of conventional rechargeable batteries which could be used in transport applications to reduce emissions, or as a 'backup' for alternative energy to allow very high levels of renewable energy in the

UK's energy mix. Nanotechnologies are likely to be employed in developing supercapacitors, which provide alternative methods of electricity storage.

- **Photovoltaics:** It is likely that nanotechnology will either reduce the cost of current state of the art solar cells or improve their efficiency. One of the largest barriers preventing the use of solar cells in a distributed network is the cost and pay-back time associated with the solar cells. Nanotechnology could provide a practical solution to this problem.
- **Thermovoltaics:** New nanomaterials may provide a means of turning waste heat into electricity. This could result in significant energy savings in any application where combustion is the primary method of energy generation.
- **Hydrogen storage:** The key to developing hydrogen as an alternative energy carrier is the development of a suitable hydrogen storage material. This is likely to involve nanotechnology either as assembled structures or to increase the surface area of a hydrogen absorbing material.
- **Hydrogen generation:** Hydrogen is an energy carrier, not an energy source. A sustainable method of hydrogen generation will be required to realise a sustainable hydrogen economy. This may be achieved through new nanostructured materials which use light to split water or by using renewable electricity and nanostructured electrical catalysts.
- **Fuel cells:** Nanotechnology is integral to the development of fuel cells. Either as part of a sustainable hydrogen economy or as efficient hydrocarbon based fuel cell, there is potential to reduce vehicular emissions or, as CHP plant, reduce heating and electricity generation emissions.

3.1.2 Water, air and land quality

These technologies have the potential to reduce the number of toxins present in our environment. Unlike GHGs, which are a truly global issue, these technologies are concerned with more localised environmental issues. Such nanotechnologies are concerned either with the reduction or elimination of toxic compounds from a process, or removal of toxic compounds from our environment.

- **Environmental sensors:** It is important to have accurate baseline data from which informed decisions on environmental issues can be made. The use of nanomaterials could produce highly sensitive sensors which could then be used to improve the quality of the local environment. The use of these sensors alongside fertiliser application may lead to a reduction in nitrous oxide releases from agriculture, which is a major cause of GHG emissions.
- **Remediation:** It is important to develop an efficient and cost effective method of land remediation. Nanofiltration technologies are being

developed to remove toxins selectively from contaminated land and air. Experimental nanofilters are also being developed to purify contaminated industrial and domestic water.

- **Agricultural pollution reduction:** Inspired by the pharmaceutical industry, smart nanoscale delivery techniques, such as nanocapsules, are being developed. The nanocapsules contain an active herbicide or pesticide. These materials can be tuned to release their payload under certain environmental conditions or as a 'slow release', which results in a reduction in the amount of agrochemicals used on the crop.
- **Water purification:** The use of reverse osmosis, which uses nanoporous membranes, could increase supply of water in areas where there are fresh water shortages.

3.1.3 Energy efficiency

These technologies are primarily concerned with improving the efficiency of energy using devices. This could result in a decrease in GHG emissions due to the close link between energy and GHG emissions.

- **Insulation:** There is a need for a convenient method for insulating non-cavity-walled buildings. A significant amount of energy is lost through the walls of both residential and commercial premises. Nanotechnology could deliver an easy to apply solution to this problem. Nanotechnology is also being employed in thin film technologies to improve the insulating properties of windows.
- **Lighting:** Light Emitting Diodes (LEDs) offer an energy efficient alternative to conventional incandescent light sources. Nanotechnology is being employed to develop these new light sources.
- **Engine/fuel efficiency:** The use of nanoparticulate fuel additives could reduce fuel consumption in diesel engines and improve local air quality. Nanomaterials are also being used to improve the heat resistance of aeroplane turbine blades allowing the engine to run hotter, which improves the overall engine efficiency.
- **Lightweighting:** The use of novel nanotechnology high strength composite materials could reduce the weight of materials. In transport applications, the use of these materials could result in GHG emission savings in both vehicular weight and packaging.
- **Novel materials:** There are a wide range of novel materials being developed which could have some environmental benefit. These range from lubricants to ultra hydrophobic coating which reduces icing of wind turbine blades. Due to the diverse nature of these compounds and, in most cases, the environmental benefit being a secondary effect, the materials have been excluded from the further discussion on ranking.

This list is not exhaustive but hopefully represents current thoughts on the major areas where nanotechnologies may provide environmental benefit. As with all experimental technologies the list will undoubtedly change as new discoveries are made. Due to the constraints of the project a thorough review and analysis of all of these areas is not possible. However it was important to ensure that the nanotechnologies which had the potential to have the highest environmental impact were chosen. To achieve this each area was ranked to show its potential environmental impact.

3.2 Ranking Methodology

3.2.1 Introduction

It is clear that the early stage development of some of these technologies does not allow accurate assessment of their potential environmental benefits. Thus comprehensive ranking of these technologies is not possible. This section will set out the criteria for the ranking of, and ultimate selection from, these technologies.

Several factors must be addressed to ensure that the environmental impacts of these technologies are accurately mapped. The potential effect of large scale adoption of these products over the current base level is the starting point. However this must be moderated against other state of the art technologies that may offer similar or better environmental performance (and which themselves may be at an experimental stage). If these alternative technologies are considered to be more promising then technological or policy options may be better tailored to support these options over nanotechnology. Conversely it is likely that in certain areas nanotechnology will deliver substantial advantages or be the enabling technology which allows realisation of the environmentally beneficial technology.

Other factors outside direct environmental performance may result in nanotechnology being favoured. For example nanotechnologies could result in a cost reduction which provides more wide scale adoption of a technology but does not have any other discernable advantage. Again, due to the experimental nature of these technologies, accurate assessment is difficult.

In essence, the report cannot examine the environmental benefit of the nanotechnology in isolation but instead must compare this technology with other promising alternatives. These factors will be easier to estimate with relatively near market nanotechnologies which are direct replacements for traditional technology. The environmental benefits of technologies which result in substantial changes in societal, technological or governmental structure are more difficult to assess. In these cases, where accurate data on alternative technologies is unavailable, predictions of the environmental benefits of future nanotechnologies will be less accurate.

It is probable that, due to the early stages of development of certain of these technologies, some of the currently claimed benefits will fail to either partially or wholly deliver. Reasons surrounding this could be that the technology will not deliver the expected advancement; emergence of unexpected problems; initial over optimistic estimation of benefits; government, industry or market forces could choose a competing technology; or infrastructural changes could be formidable. It is important that this feasibility is examined when selecting promising environmentally beneficial technologies.

3.2.2 Metrics

Environmental metrics

The Millennium Goals, the UK Sustainable Development Indicators and the UK Sustainable Consumption and Production Indicators were used to determine key metrics in analysing the potential benefits of nanotechnology. Table 1 below summarises relevant environmental issues.

Table 1: Summary of governmental environmental indicators

Millennium Goals (Env.)	**UK SD Indicators**	**A selection of UK SCP Indicators**
Energy use/ $ GDP	GHG emissions	GHG emissions
CO_2 emissions/person	Resource use	Aviation and shipping emissions
CFC consumption (ODP, tonnes)	Waste	Household energy use
Access to improved water sources	Environmental quality	Road transport emissions (CO_2, NO_x, PM_{10})
Improved sanitation		Resource use
Access to secure tenure		Water resource use
		Water consumption
		Fertiliser use, NH_3, CH_4 emissions
		Waste
		Emissions of air pollutants
		River quality

From this list, where possible, we have merged these indicators and selected three broad environmental measures which fit best with Defra's environmental agenda. These are:

- GHG emissions
- non-GHG emissions
- resource efficiency.

Estimates of the benefits of nanotechnologies must involve issues raised in the previous section. However, meaningful comparisons or weightings between these issues are extremely difficult. Therefore decisions on ranking based on all three measures are likely to have a degree of subjectivity.

The recent letter from the Prime Minister to David Miliband outlining Defra's key policy challenges highlighted climate change as the most important area.[a] To this end, this report will focus on those environmentally beneficial nanotechnologies which could have the highest impact on the UK's GHG emissions. David Miliband's response highlights the environment as the most important challenge facing the department and identifies climate change as a key issue.[b] Thus the metric of GHG reduction forms the primary metric in this report for the development of a ranking system for environmentally beneficial nanotechnologies.

To aid in the transparency of the ranking process values between 1 (low) and 5 (high) were assigned to GHG reduction. These are estimated incremental benefits offered by nanotechnology over other competing technologies. The ranking is assigned in Table 2:

Table 2: Ranking score for potential greenhouse gas emissions savings in the UK

Ranking score	Maximum potential UK GHG reductions per annum (CO_{2E})
1	<1 Mte
2	<5 Mte
3	<10 Mte
4	<20 Mte
5	>20 Mte

These numbers are necessarily very approximate estimates. Where possible the values have been drawn from other research and, in the

[a] Open minute between the Prime Minister and David Miliband, May 2006
[b] Open minute between David Miliband and the Prime Minister, June 2006

absence of definitive figures, assumptions on the development of the rankings and the potential reductions in GHGs are stated clearly.

Information on potential reductions in non-GHG emissions and improvements in resource efficiency will also be discussed. However in addition to the inability to compare the three metrics directly, both resource efficiency and non-GHG reductions incorporate a wide variety of components and any meaningful comparisons are difficult. For example the difficulties in comparing one tonne of mercury to 100 tonnes of concrete from a resource efficiency perspective.

Feasibility

Virtually all identified examples of potentially environmentally beneficial nanotechnologies are either in development stages or early commercialisation. Therefore by their very nature there is a degree of uncertainty as to the extent to which these technologies will succeed in the market place. The feasibility of these technologies is reliant on:

- distance to market
- competition from alternative technologies
- infrastructural changes required to implement the technology effectively.

Feasibility is therefore a measure of the effort (political, social, infrastructural or research) required to realise the full benefit of the technology.

Distance to market expresses the likely development time the nanotechnology will require prior to the realisation of a viable product. Within this it is clear that the technologies which are near to market are, by definition, more likely to lead to viable products than early stage prototypes.

Competition from alternative technologies gives an indication of the chances of success in the marketplace. If the nanotechnology is trying to enter an already crowded marketplace the benefits and cost of the technology must be carefully marketed to compete with alternatives. Conversely, a nanotechnology which provides a solution where there are few viable alternatives is likely to have a greater chance of success.

Changes in infrastructure comprise the overall changes (in terms of society) which will be required to implement the technology. This is a complex area and any measure is likely to be qualitative. A product which requires minor infrastructural changes is likely to be a direct 'drop in' replacement for a current product, whereas a nanotechnology which requires large scale investment in surrounding infrastructure or significant changes in the public's behaviour can be considered to have high infrastructural changes associated with it. Nanotechnologies which require small infrastructural changes are consequently more feasible.

Absolute values cannot be attributed to the feasibility of individual technologies; however for the purposes of the report a transparent ranking of the feasibility of these technologies is required. Table 3 below outlines the metrics used to determine feasibility of the technology. As far as possible, qualitative assessment of these components of the metric are achieved through engagement with experts and literature. Ultimately, when attempting to predict the 'feasibility' of any future technology, the metrics are, to some degree, subjective.

Table 3: Description of the metric used to determine the feasibility of a nanotechnology.

Metric	Rank	Description
Distance to market	1	Still in early developmental stage, unknown if suitable for commercialisation (>10 years from full commercialisation).
	3	At the prototype stage, further developmental work required (<10 years from full commercialisation).
	5	At (or very close to) commercialisation (<5 years from commercialisation).
Competition with alternative technologies	1	The market place is crowded with cheap alternatives.
	3	There are a few potential alternatives available but they may be unsuited, expensive or still in development.
	5	This nanotechnology appears to be the front runner to deliver this benefit.
Infrastructural changes	1	Substantial investment required to begin to see benefits. Comparable with the scale of investment in renewables by the energy sector.
	3	A measured amount of investment is required to adopt the new technology, for example the switch to unleaded petrol.
	5	'Drop in' replacement - the nanotechnology can be fully implemented without necessarily resulting in any infrastructural changes, for example energy saving light bulbs.

For simplicity, the metrics above will be ranked either 1 (low), 3 (medium) or 5 (high) whereas the overall feasibility of the nanotechnology is ranked out of 5 (5 very feasible, 1 very difficult) and will comprise all three metrics listed above. To determine a value for feasibility, scores for all three metrics will be summed and the value will be determined by the data range in Table 4.

Table 4: Overall feasibility score

Summed values	Feasibility score
<6	1
<8	2
<10	3
<12	4
>12	5

3.3 Ranking

It is clear that although hydrogen storage, hydrogen generation and hydrogen fuel cells are distinct technological areas, success of the hydrogen economy is dependant on all three technologies. If the hydrogen economy is to be considered for political or technological focus then all three areas of the system must be addressed. Therefore hydrogen storage, hydrogen generation and hydrogen fuel cells were combined under the heading of the hydrogen economy and the remaining fuel cell technology was placed under the heading of fuel cells.

The nanotechnologies were scored against the ranking criteria described above. The outcome of this process is summarised in Table 5. Justification for these scores is described in detail in Appendix 2.

It is important to note that the ranking in the table below is only a reflection of the ability of the nanotechnology to deliver a reduction in GHGs. Although undoubtedly environmentally beneficial, certain technologies are not oriented to reducing GHG emissions and therefore perform badly within the context of this report. However, these technologies may provide greater benefits under alternative metrics and should not necessarily be considered 'poor' environmentally beneficial nanotechnologies.

Table 5: Ranking of environmentally beneficial nanotechnologies

Rank	Technology area	Distance to market	Competition with alternative tech	Infrastructural changes	Feasibility	GHG reduction	Feasibility × reduction	Feasibility + reduction
1	Electricity storage	3	3	3	3	5	15	8
1	Engine efficiency	5	5	5	5	3	15	8
2	Hydrogen economy	3	3	1	2	5	10	7
3	Photovoltaics	3	3	3	3	3	9	6
3	Insulation	3	1	5	3	3	9	6
4	Thermovoltaics	1	5	1	2	4	8	6
4	Fuel cells	5	3	3	4	2	8	6
4	Lighting	5	3	3	4	2	8	6
5	Lightweighting	3	1	5	3	2	6	5
6	Agriculture pollution reduction	5	3	5	5	1	5	6
7	Drinking water purification	5	1	3	3	1	3	4
8	Environmental sensors	3	1	3	2	1	2	3
8	Remediation	3	1	3	2	1	2	3

3.3.1 Selection of nanotechnologies for further study

Initially the score for GHG emissions was summed with feasibility; however this led to poor resolution between the different technologies. To address this, the score for GHG emissions was multiplied by the feasibility score. This increased the spread of marks and penalised technologies which were strong in only one category, but did not change the ranking order significantly.

To ensure that this methodology is robust it is important to 'sense check' the ranking with the knowledge collected in this initial scoping work:

- Batteries, specifically for transport applications, have the potential to significantly reduce GHG emissions, and any new technologies should be relatively easy to roll out.
- Using nanotechnology to improve engine efficiency is a relatively facile process which could result in moderate emission savings.
- The hydrogen economy is similar to electricity storage but its implementation is likely to be more complex, however potentially it does solve issues of range associated with electric powered vehicles.
- In the UK, photovoltaics are likely to play only a small part in contributing to the energy mix. However it is likely that nanotechnology will be involved in developing the next generation of solar cells.
- The development of a viable and convenient method for insulating non-cavity walled dwellings would significantly reduce heat loss and therefore emissions from heating. Thin film coatings and paints which incorporate nanotechnology are a possible solution to the problem.
- Thermovoltaics could potentially save a significant amount of energy, however the research into these materials is at an early stage and therefore development of nano-enabled technologies may stall.
- Experimental fuel cells are beginning to be commercialised and large CHP plant could result in significant emission savings, however this technology must compete with conventional CHP.
- The integration of LEDs into domestic and commercial lighting should be relatively easy. However the overall benefit of using these devices over competing technologies is relatively modest.
- The use of novel materials is likely to lead to lighter vehicles and a reduction in loads transported throughout the UK. The additional benefit of using nano-enabled technologies over potential state of the art is, though, less well defined (other than speculation for the long term development of advanced nanocomposites).
- Agriculture pollution reduction, drinking water purification, environmental sensors and remediation have environmental benefits other than GHG reduction and therefore score poorly in this measurement.

Based on this analysis, five areas were chosen for further research:

- electricity storage
- engine efficiency
- insulation
- hydrogen economy
- photovoltaics.

This list also represents a spread of near (engine efficiency), medium (electricity storage, insulation and photovoltaics) and long term (hydrogen economy[a]) technologies, which hopefully provide a representative spread of the issues that are likely to surround emerging nanotechnologies.

[a] Although the technology is at the prototype stage the large infrastructural changes required to supply hydrogen to fuelling pumps makes this technology a long term investment.

4 Analysis of EBNTs

This section investigates the five environmentally beneficial nanotechnology areas identified in Section 3.3. The focus of this section is to identify the main barriers surrounding the nanotechnologies, the current state of the art and potential solutions to enable the development of the environmentally beneficial nanotechnologies.

4.1 The Hydrogen Economy

4.1.1 Overview

Hydrogen (and oxygen as a by-product) can be generated through electrolysis or directly catalysed decomposition of water. Hydrogen can then potentially be stored indefinitely, although its small molecular size and gaseous nature make storage difficult when combined with the need for substantial energy densities. Using fuel cells, hydrogen can be reacted with oxygen (usually from the atmosphere) to generate water and usable electricity. Nanotechnology is likely to be a key component in generation, storage and use of hydrogen as a fuel source. If the electricity used to generate the hydrogen from water is produced via renewable means, this system could be used to store and transport excess electricity. Hydrogen has the potential to replace traditional hydrocarbons as the major source of energy in the UK.

Hydrocarbons are excellent energy storage media. A huge amount of research and effort has been devoted to utilising this energy source, which has formed the bedrock of modern society. Without hydrocarbons, it is likely that modern society as we know it would not exist. It is clear why these materials have been the energy source of choice for nearly two centuries: until recently, they have been in abundant supply; they have a very high energy density; they are easy to transport and control and, other than obvious flammability issues, are relatively benign. The primary energy infrastructure of western society has been developed to deliver these fuel stocks as liquids for transportation and as solids and gases for use in electricity generation and household space and water heating. The logistical and economic costs of changing this system of energy storage and delivery are likely to be great. However significant changes to this system are imperative if the UK is to reduce its dependence on this non-renewable energy source significantly. The reasons for this have been widely publicised; UK North Sea oil is rapidly dwindling, forcing us to source oil and gas supplies from less secure locations; also the potential global environmental impact of releasing 25 billion tonnes[a] of carbon dioxide into the atmosphere from the combination of these fuels.

Hydrogen as an energy source

Hydrogen has been proposed for several decades as an alternative energy source to hydrocarbons. It is the most abundant material in the universe but on earth most hydrogen has reacted with oxygen to form water. Hydrogen must be considered an energy carrier, as electricity is, not an energy source and thus must be generated from another available energy source. Hydrogen can then either be burnt in a combustion chamber like conventional fuel or used in fuel cells to be catalytically reacted with oxygen over a fuel cell to generate electricity and water as a by-product.

There are three stages to this process where nanotechnology is likely to play a leading role:

- the generation of hydrogen from water
- the storage of hydrogen
- the controlled reaction of hydrogen with oxygen to form electricity (fuel cell).

If renewable or low carbon energy is used to produce hydrogen, the energy cycle can be considered low emission and reduce our impact on the environment.

The way in which nanotechnology may impact these three technology areas is outlined below.

Hydrogen generation

Hydrogen itself is merely an energy carrier and not an energy source. There are no significant quantities of exploitable hydrogen available for use as a fuel source. Therefore to use hydrogen in fuel cells, it must first be generated from a different feedstock. The current industrial method for hydrogen production involves partial oxidation of methane (known as steam reformation of methane). This process converts methane into hydrogen and carbon dioxide. Using this process, eleven tonnes of carbon dioxide are produced for every tonne of hydrogen.

A projection from the Tyndall centre has shown that, in the short term, use of steam reformation of methane is likely to predominate in the generation of hydrogen. There is likely to be an initial increase in net carbon emissions

[a] Climate Change 2007: The Physical Science Basis, Intergovernmental Panel on Climate Change, 2007.

if a hydrogen infrastructure is developed. However this is seen as a necessary compromise to facilitate rapid deployment of a cost competitive hydrogen network. Obviously any emission reductions are limited when simple gas reformation is used. To reduce the CO_2 impact on gas reformation there is the potential option of sequestering the emission

Although the methane would be from non-renewable sources, using it as an energy feedstock will reduce the UK's dependence on crude oil and increase dependence on sources of natural gas with consequent changes in the nature of geopolitical risk.

There is also the potential to generate H_2 via fermentation of organic waste using strains of yeast or bacteria. However current estimates are that it is unlikely that this supply of bio-hydrogen would meet world demands for a full scale hydrogen economy.

Hydrogen generation via electrolysis

This method electrically charges two plates containing a catalyst which converts water into oxygen and hydrogen. Nanoparticles and nanostructures on the surface of these plates can increase the overall efficiency and speed of this process. This technique could reduce the cost of developing an extensive hydrogen transport network by greater production of hydrogen by the end user.

The distribution of hydrogen either via tanker or through pipelines can result in large losses through leaks. Hydrogen also embrittles steel, leading to high capital investment in specialist materials or high maintenance costs. In terms of transport this presents a serious problem; there are approximately 10,000 forecourts and supplying these with hydrogen would difficult and expensive. The current gas pipeline is unsuitable for the transportation of hydrogen and the costs to develop a new network will be high (£1 million per mile).[a] Potentially, electrolysis could circumvent this issue by delivering energy via the national electricity grid directly to the fuelling stations where hydrogen could be generated via electrolysis on demand. Obviously there would be an initial increase in capital to install an electrolyser, but problems of transportation and large scale storage of hydrogen are removed. There would also be increased strain on the national grid; however, electricity transportation is a mature technology, and the problems of increased demand are not likely to be technically demanding (although they could be extremely costly). It has been estimated that sourcing hydrogen for transport through electrolysis would

[a] Source: H_2 net.

double the UK's electricity demand, leading to a corresponding increase in demand on the national grid.[a]

To be sustainable, this system must use electricity generated from low carbon sources. The recent energy review suggests that over the next 15-20 years low emissions electricity will be generated via nuclear power, renewable energy sources, Carbon Capture and Storage (CCS) coal and gas fired power stations. Although outside the scope of the report, this is an area of significant interest and is discussed elsewhere.[b,c]

Hydrogen generation from photolysis

Certain materials have been shown to split water into hydrogen and oxygen in the presence of sunlight. These photoelectric cells perform in a similar way to electrolysis cells but use sunlight as the energy source. The barrier to the development of these cells is developing a material which will effectively harness the sun's power whilst being stable enough to survive for an acceptable lifetime. Hydrogen Solar, a UK based company, is developing a solar cell that splits water into hydrogen and oxygen using nanostructured materials. This cell design is approximately twice as efficient as most other experimental devices available and is being commercialised. There are several academically based research projects utilising chemistry to develop chlorophyll mimicking molecules which generate hydrogen from water using sunlight. This research is at relatively early stages but may, in the long term, prove to be a cheap source of hydrogen.

Recent research into porphyrin (a common molecule used by plants in photosynthesis) nanotubes with particles of platinum coated onto their surface has shown promise as an effective catalyst for photolytic splitting of water.[d] Although in its early stages, there is the potential for nanotechnology to provide a solution from an unexpected avenue.

Hydrogen fuel cells

Fuel cells use catalytic reactions to generate electricity directly from a chemical fuel source. Hydrogen fuel cells operate thus:
1) A catalyst splits hydrogen into a proton and an electron.

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[a] Based on data from the Hydrogen World Ltd website (10 GW = 4m cars), transport statistics of DfT (32m cars in Britain) and approx 100GW installed capacity
[b] The Stern Review: The economics of climate change, 2006.
[c] The Energy Challenge: Energy Review Report 2006**,** Department of Trade and Industry
[d] "Photocatalytic Nanotubes" Zhongchun Wang, Craig J. Medforth, and John A Shelnutt, 2005, Sandia press release.

2) A membrane selectively allows the proton to travel through it whilst preventing the electron from doing so, so that the electron travels through a copper wire to generate an electrical current.
3) A second catalyst on the other side of the membrane combines the proton with the electron and oxygen to form water.
Unlike traditional electricity generation which uses gas turbines the overall efficiency of the system is significantly improved, with commercial fuel cells having efficiencies of up to 50%.[a] Current state of the art hydrogen fuel cells use platinum as a catalyst and a nanoporous polymer Proton Exchange Membrane (PEM) as the membrane.

As a general rule, the larger surface area, the more active the catalyst. The catalytic activity can be maximised by nanosizing the particles of catalyst. Such a technique is being employed to reduce the cost of catalyst materials. Manufacture of these nanoparticles will, to some extent, depend on the materials used in the fuel cell. However this is currently not perceived to be a significant barrier in producing fuel cells. Nanosizing the catalyst is considered as key to the development of efficient hydrogen fuel cells. There are well documented concerns[b] that the quantity and cost of platinum required to produce large numbers of automotive fuel cells will prevent their large scale adoption. Although currently still in the experimental stage, these concerns are being addressed. As a direct result of using nanotechnology in producing and controlling nanoparticles, the quantities of these rare metals used in the manufacture of catalysts are constantly being decreased with little loss in performance. Carbon nanotubes are being utilised as supports for the catalysts. It is believed that the use of these nanomaterials can reduce the amount of platinum, and hence cost, of the fuel cell. Also, several alternatives to platinum are being developed which may help to address this problem.[c]

Industry experts now see the Proton Exchange Membrane as the most expensive component of a state of the art fuel cell. The development of cheap, efficient membranes for controlling the flow of protons is an important challenge. The goal currently is to develop a nanoporous membrane which is robust to temperature fluctuations and tolerant to impurities in the fuel supply.

Hydrogen storage

Hydrogen is light and has a high energy value. However hydrogen is a gas and therefore needs to be compressed to be stored in a practical volume.

[a] Efficiency of Hydrogen Fuel Cell, Diesel-SOFC-Hybrid and Battery Electric Vehicles, European Fuel Cell Forum, 2003.
[b] http://www.platinum.matthey.com/applications/fuelcells.html
[c] Breakthrough research on platinum–nickel alloys, ALSNews, February 28, 2007

The current most volume efficient method of storing gases is through liquefaction. Hydrogen liquefies at -260° C. This process is energy intensive but achievable on an industrial scale. Storage for stationary applications, where weight and volume are less critical, could be achieved using conventional high pressure cylinders or, potentially, subterranean caves. Current hydrogen powered demonstration cars use large pressurised insulated flasks to carry liquefied hydrogen fuel. These are significantly larger than a standard petrol tank, which leads to a loss in boot space.

A practical and efficient method of hydrogen storage must be found to allow mainstream deployment of fuel cells in transport. Research is being undertaken to use 'hydrogen carriers' as a fuel source. Promising materials include formic acid and methanol. These materials are 'reformed' over a separate catalyst to form hydrogen and (usually) carbon dioxide.

Significant nanotechnology areas

Light metal hydrides

Light metal hydrides react with hydrogen, essentially encapsulating the hydrogen on the surface of the compound. To maximise hydrogen absorption, such materials are likely to be in the form of nanopowders or nanoporous matrices to expose the largest surface area to hydrogen gas. Therefore nanotechnology is integral to this method of hydrogen storage.

This method of storage is seen as potentially the most efficient storage mechanism for hydrogen. An important advantage of this technology is that hydrogen can be stored at near ambient conditions reducing the energy requirements for storage associated with high pressure or cryogenic storage. However, despite its promise, the state of the art in this area has failed to meet the US Department of the Environment's target of 6.5 wt% uptake of hydrogen. The US government expected this to be met by 2010, but sectors of the industry are sceptical that this performance will be achieved by this deadline.

Although nanotechnology is integral to development of this storage media, its use must come after the development of the correct materials. Without the synthesis of lightweight, high capacity materials the development of nanomaterials is redundant. Following this fundamental research there are barriers to the development of these materials into working prototypes. The majority of the research into metal hydrides is being performed by physicists, chemists and material scientists. Anecdotally, better integration between these researchers and product developers will ensure that promising materials can find appropriate applications.

A major barrier to this system will be in the cost of synthesizing some of these novel materials. These lightweight compounds are comprised of expensive materials and are generally synthesised using high temperatures and pressures. Even in the event that a candidate material is developed there will be significant issues in bringing it through to commercialisation. In addition, the environmental burden of producing these materials may have a significant impact on the overall LCA of the system.

Carbon nanotubes storage

Considerable time and effort has been invested into utilising carbon nanotubes as a hydrogen storage media. This material was initially reported as a potential solution to the problem of storage with high levels of reversible hydrogen absorption. However further investigation determined that this was not the case, perhaps an example of a nanotechnology application over-hyped in its early stages. It is now commonly thought that carbon nanotubes themselves will not solve the problem of storage.

In an annex to this work, there are several research groups investigating hybrid carbon nanostructures which have the potential to store large quantities of hydrogen. This work is still some distance from prototype development.

Molecular sponges

Researchers are developing molecular cage structures that absorb hydrogen into their structure in a similar manner to a sponge holding water. These compounds are large molecular assemblies with structures similar to honeycomb and pore sizes in the nanometre range. In theory, hydrogen can be absorbed into the material and released by variations in pressure or temperature. Research is currently at the experimental stage; the main target is to achieve a 6 wt% uptake of hydrogen into the system, which current research is some way off achieving. These materials are being developed by chemists using molecular building blocks. The materials are being assembled through chemical reactions.

Potentially, hydrogen could be used in both static distributed CHP applications, which would store excess energy for peak use and to power land based transport.

Domestic and commercial electricity generation

To assist the development of a sustainable electricity generation infrastructure with a high proportion of renewable power, an efficient and cheap method of energy storage must be developed to store excess energy for use during periods of high demand. Potential solutions include chemical storage or high capacity batteries. High capacity batteries are discussed in Section 4.3. Chemical storage, namely using hydrogen, has received a significant amount of interest. Hydrogen could be generated via electrolysis for storage and then reacted to generate electricity during high demand periods.

The use of hydrogen generated via electrolysis for stationary power will always be less efficient than direct electricity delivery. However it is likely that this method of energy storage and delivery will become more important in the long term as renewable energy becomes more important in the UK's energy mix.

Hydrogen for transport

Developing a low carbon transport system has become more important in recent years, as the percentage of transport GHG has grown.[a] The three main contenders to provide this vision are:

- fuel cells
- biofuels
- electric battery power.

In the near term, biofuels and hybrid vehicles appear likely to take a lead in reducing CO_2 emissions from transport. Hybrid vehicles will result in a 15 % emissions saving but still rely on fossil fuels for their energy source. The UK government has set a target to increase the usage of biofuels (which, like for like, reduce GHG emissions from transport by approximately 40% but increase other non-GHG emissions)[b] in transport to 5% of diesel and petrol consumption by 2010. Ultimately however, limitations on available arable land are likely to limit the utilisation of this renewable feedstock.[c] The use of hydrogen in vehicular fuel cells, along with battery powered vehicles (discussed in section 4.4), are seen as lead candidates as the far term sustainable replacement for fossil fuel powered combustion engines. The advantage of this hydrogen system is that water is the only emission from the exhaust of the vehicle. Also, assuming the H_2 is generated via renewable means, the entire process is potentially carbon neutral.

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[a] Greenhouse gas emission trends and projections in Europe, European Environment Agency, 2006.
[b] "Comparison of LCA and external-cost analysis for biodiesel and diesel", L. De Nocker, C. Spirinckx and R. Torfs, 2nd International conference LCA in Agriculture, Agro-industry and Forestry, 1998
[c] www.monboit.com

The wide scale use of H_2 powered vehicles is, however, still a considerable distance away and there is therefore a significant possibility that the technology will not achieve its potential or an alternative technology will become dominant. Full scale production of H_2 vehicles is estimated to be at least ten years away. The technology is mature enough to see Honda develop a hydrogen powered concept car, but this prototype is seen as a demonstration unit and publicity campaign rather than a main stream production model. Several hydrogen powered motorbikes are also at the prototype stage, for example the ENV motor bike is expected to enter production within the next two years.

The Bush administration is investing heavily in developing hydrogen as a viable fuel source for transport. The hydrogen fuel initiative budget has increased nearly fourfold in seven years from $73m to $289m. There is an inherent risk in development with all prototype technologies, however the level of investment in the USA may provide a strong enough market incentive to pull hydrogen fuel cells through to the mainstream.

Despite the problems of storage discussed above, hydrogen is considered the lead fuel cell candidate for fuel cell powered vehicles. Direct methanol fuel cells use liquid methanol as the fuel source but generally have low energy outputs making them unsuited for transport applications. Large solid oxide fuel cells which can generate sufficient power and can be fuelled using fossil fuels operate at high temperatures, and require long start-up and shutdown times[a] which would be inappropriate for transport applications.

Problems for storage and use of hydrogen could be reduced by reforming methanol *in-situ*. Methanol would be stored in a conventional fuel tank and converted into H_2 and CO_2 prior to use via a hydrogen fuel cell. This process still uses hydrogen to power the fuel cell (unlike a direct methanol fuel cell) but the hydrogen is stored molecularly as methanol. In essence, methanol would be used to store energy rather than hydrogen. This has the advantage that the transportation and storage infrastructure, which in itself maybe the largest stumbling block for the hydrogen economy, is currently in place, however, the disadvantages include:

- a more complicated onboard fuel cell system
- few viable large scale methods for producing methanol sustainably[b]
- potential by-products formed during the formation of hydrogen from methanol may damage the fuel cell electrodes

[a] The ceramic materials tend to crack through thermal shock if they are repeatedly and rapidly heated and cooled.

[b] Industrially methanol is formed using fossil fuels. However, there is potential to combine methanol production with CCS. There is also the potential to form methanol via biomass

- unless renewable methanol is used, eleven tonnes of CO_2 are released from the reforming process for every tonne of H_2 used.

For these reasons, it appears that using a liquid precursor as the energy source is not favoured by the large automotive manufacturers who are heavily involved in the development of hydrogen fuel cells for transport. However if issues surrounding hydrogen storage are not resolved then this option may be revisited.

Ultimately a sustainable source of hydrogen will need to be found for this technology to have a long term future; however, it has additional benefits outside potential carbon dioxide reduction. There could be a significant improvement in city air quality from using hydrogen fuel cell powered vehicles. Unlike petrol driven vehicles, hydrogen fuel cells only emit water and could reduce significantly the quantity of air borne pollutants emitted in large cities. For example, in London, 60-70% of air pollution is from transport,[a] which is responsible for an estimated 1,600 premature deaths in the capital per annum. Therefore by reducing emissions from transport, the improvement in air quality is likely to have a positive impact on human health.

4.1.2 Potential policy implications

The end of life vehicle directive requires 85% of a car to be recycled.[b] The addition of difficult to dispose of components (such as a fuel cell or electronics) is likely to increase the cost of disposal of hydrogen powered vehicles. This could result in higher retail prices to pay for end of life treatment. It might be necessary to offset this cost of disposal against the potential benefits associated with hydrogen powered transport.

Infrastructural policies surrounding refuelling stations will need to be developed. Hydrogen at refuelling stations is unlikely to be profitable for forecourt operator for a considerable period. If issues with storage can be addressed, the incorporation of hydrogen refuelling should be made a prerequisite on major routes.

4.1.3 Route to market

The adoption of hydrogen as a fuel source is likely to be a gradual process. This is largely due to the vast infrastructural changes required to implement this technology. The financial cost is more favourable for transport (mainly road) than for use as an energy storage medium in

[a] Cleaning London's air: Highlights of the Mayor's air quality strategy, September 2002.
[b] http://www.opsi.gov.uk/si/si2005/20050263.htm

distributed electricity generation.[a] Hydrogen fuel cells are likely to remain a niche area for stationary applications for some considerable time. Hydrogen is potentially an attractive renewable energy store, however large scale deployment of renewable energy generation is required first.

To overcome issues of intermittency of supply of renewables, extra capacity is built into the electricity grid. This extra capacity results in an additional cost to supply the consumer. Currently, building and running an electricity storage facility based on hydrogen is unlikely to be cost effective compared to installing extra capacity. The intermittency of renewable energy supplies can be smoothed through connection to the national grid. Indeed, until greater than 20 % of the UK's energy mix is sourced from renewable energy, there will not be any significant problems with intermittency of supply. Current rationale is to build extra capacity into the national grid to act as a backup for times of low generation from the renewable electricity sources. However, as the percentage of renewables contributing to the UK's energy supply is increased, the economics of ensuring that there is sufficient and reliable electricity generation dictate that an electricity storage installation will be required. Therefore only at very high levels of renewable energy will there be an economic argument for sourcing energy stores such as hydrogen to reduce the cost of extra capacity.

It is important to note that energy generated from stored hydrogen will be more expensive than from primary generators. The reason for this is that energy will always be lost in converting electricity into hydrogen and back, and it is therefore, more expensive than primary electricity generation.

There are several competing technologies that may offer more attractive alternatives to hydrogen for stationary energy storage in the long term, such as high capacity batteries. [b]

The use of hydrogen to power transport appears to be a promising method for eliminating harmful emissions from transport within cities. Combined with low or zero carbon hydrogen generation, hydrogen powered cars could result in transport being decoupled from carbon dioxide emissions.

Space limitations and the problems associated with the development of a viable storage media are probably going to limit the use of fuel cells in the near term to bus services. There are, however, demonstration projects in major cities throughout Europe already.[c] As reported above, the use of

[a] A strategic framework for hydrogen energy in the UK, E4tech, 2004

[b] Regensys utility scale energy storage: overview report of combined energy storage and renewable generation, DTI, 2004

[c] CUTE project: hydrogen fuel cell bus project, Europe, 2001-2006

nanotechnology is likely to underpin the development of hydrogen storage devices and ultimately the development of wide scale deployment of hydrogen powered vehicles. The use of demonstration projects will also provide valuable 'real world' data for the development of more efficient fuel cells. The success or failure of a hydrogen economy will ultimately rely on fundamental and applied science overcoming problems from these pilot studies.

The European Hydrogen and Fuel Cell Technology Platform Deployment Strategy have developed a road map to the integration of hydrogen fuel cells into CHP and transport applications. From their study it seems clear that initial delivery of hydrogen will be via methane gas reformation which is a non-renewable feedstock. An efficient and renewable method must be found before the hydrogen economy can be considered sustainable.

4.1.4 Barriers to market

Technical

It is clear that the largest barrier to the wide scale adoption of the hydrogen economy is the discovery of a cheap and efficient method of storage. Virtually all criticisms are aimed either directly or indirectly at this area of the technology. Both generation of hydrogen via electrolysis and use of hydrogen in a fuel cell are relatively efficient, but large energy losses are experienced in all current practical methods of storage. It is likely that if the breakthrough is made it will be from material sciences and will involve nanotechnology. The ultimate goal will be a device that can store large quantities of hydrogen reversibly at near ambient conditions, however this appears to be some distance away.

There will need to be a significant shift in the UK's infrastructure to accommodate a new method of energy storage and delivery. There are several different scenarios for this.[a] In the short term hydrogen generation will occur via steam reformation and be delivered to specialist suppliers through high pressure tankers on road vehicles. In the mid to long term there are likely to be three different methods for the transportation of hydrogen for use in vehicles (Table 6).

[a] The hydrogen energy economy: its long-term role in GHG reduction, Geoff Dutton, Abigail Bristow, Matthew Page, Charlotte Kelly, Jim Watson and Alison Tetteh, January 2005

Table 6: Scenarios for hydrogen generation

Description	Advantages	Disadvantages
Tanker supply. Hydrogen is delivered to forecourts using high pressure tanker deliveries.	Easy to implement. Uses current infrastructure.	Potentially too expensive and inefficient for wide scale adoption.
Dedicated pipeline network of hydrogen.	Very high capacity and potentially efficient method of transport.	Huge cost. Potential issues of leaks.
Distributed hydrogen production using electrolysis.	Can produce hydrogen on demand. Low energy transportation.	Extra strain on the national grid.

All potential methods of delivery are likely to involve significant costs and the most effective method will depend on the scale of adoption. Therefore the final decision on the delivery of hydrogen to forecourts is likely to be deferred until the success (or potential failure) of hydrogen powered transport is proved.

Other than the technological barriers of hydrogen fuelled transport the overall costs of the 'engine' compared to a conventional internal combustion engine are expected to be significantly higher. The majority of hydrogen powered vehicles are leased from car manufacturers and are not a true indicator of the cost of production models. It is likely that, certainly in the short to medium term, hydrogen powered vehicles will not be cost competitive with the equivalent fossil fuel powered alternatives, either in terms of initial capital outlay or cost of fuel. Therefore wide scale adoption of this technology will probably require fiscal incentives such as congestion charge reductions.

Social

Nanomaterials used in transport are likely to be either trapped or encased well away from the user, with consequent reduction in risk. However there may well be great concern with the use wide spread use of hydrogen. It is an explosive gas and critics have suggested that it will pose too great a threat to the general public. Discussion on this topic has been covered in greater detail elsewhere.[a]

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[a] www.rmi.org

There will be a growing need to develop methods of utilising components containing nanotechnology at the end of the product's life. With the exception of service personnel, exposure to the nanotechnologies during the lifetime of the fuel cells is likely to be low. However current recycling methods may not be suitable for the correct disposal of the fuel cells and storage systems. This issue must be addressed if wide scale adoption of these technologies is to be realised.

The use of nanoparticles in a fuel storage device creates the technological challenge of encasing them within a suitable fuel tank. By their very nature, containment of the nanopowders is difficult. Effective filters to ensure that the nanomaterials are sufficiently encased in the fuel tank are important to reduce risk of exposure to nanomaterials, protect the fuel cell from contamination and improve the lifetime of the hydrogen storage system.

4.1.5 Recommendations

Public transport and the creation of niche markets

The small scale trials of hydrogen powered bus fleets appear to be successful.[a] Until issues with the efficient storage and transport of hydrogen are resolved, the use of hydrogen powered buses appears to be an effective market pull. Hydrogen powered transport is considerably more expensive that the equivalent diesel bus. Therefore any further near term development of this system is likely to require financial assistance. This, coupled with the ability of local and regional government to work closely with bus fleet operators, could place the UK in a promising position as a major market. Rather than specifying specific technologies, such schemes could take the form of introduction of 'zero' emission vehicles. Such a scheme would be open to several different technologies, such as battery powered transport and trolley buses, but hydrogen vehicles could be a competitive technology.

The specification of such zero emission vehicles for public transport in urban areas has been proposed as have methods of creating 'strategic niches' through which system-wide innovation can be introduced.

Fundamental research

It is clear that there is still need for fundamental research into this area. Fuel cell and hydrogen storage development is largely the realm of chemists, physicists and engineers either in universities or in the research laboratories of large corporations, such as Johnson Matthey. In terms of

[a] CUTE project: hydrogen fuel cell bus project, Europe, 2001-2006

fundamental research the UK is able to, and does, compete on the world stage. Although there are no major UK based automotive companies, the international nature of the industry is likely to facilitate the introduction of any UK based materials into hydrogen powered vehicles and is not seen as a major barrier to researchers. The new diamond synchrotron at Harwell, the UK's largest funded scientific facility for 30 years, will provide the tools to assist us to compete internationally. There may also be a role for these technologies in the upcoming DTI funded energy technologies institute.

Cultivation of links with industry

Anecdotally, the lack of a large multinational automotive company based in the UK inhibits collaborative research. Inward investment from multinationals should be encouraged through high level engagement (probably led by the DTI).

4.1.6 Potential environmental benefits

Using conventional methods of hydrogen generation, the GHG reductions from developing a hydrogen economy for transport range from approximately 50 % to virtually nil. Indeed, there have been studies which suggest that a hydrogen economy for transport based on steam reformation would lead to an increase in the UK's net GHG emissions.[a] Even assuming that there is not a net GHG benefit, there will be a net reduction in localised city emissions of SO_x, NO_x and particulates. As described above, this will result in a significant local environment and public health benefit. A 25 % fall in emissions would result in an approximately 29 Mte of carbon dioxide reduction. The generation of clean hydrogen, either through CCS, renewable electricity electrolysis or through fermentation processes could potentially decouple GHG emissions from transport. In essence, this could lead to significant reductions in emissions from road transport equivalent to approximately 120 million tonnes based on current emissions. Projections by the Tyndall centre[b] suggest that this is feasible but they also show projections with more modest emission savings.

Hydrogen itself is an 'indirect' GHG, therefore the global warming potential from hydrogen emissions through leaks must be acknowledged. Replacing the entire UK fossil fuel based energy system requires 4.8 million tonnes of hydrogen.[c] If 10% of hydrogen is lost through leaks we calculate that this would still give a 94% reduction in global warming emissions.[d]

[a] Does the hydrogen economy make sense?, European fuel cell forum, Alf Bossel, 2005.
b The hydrogen energy economy: its long-term role in GHG reduction, Geoff Dutton, Abigail Bristow, Matthew Page, Charlotte Kelly, Jim Watson and Alison Tetteh, January 2005
[c] http://www.hydrogen.co.uk/h2/euro_quebec_h2project.htm
[d] ENDS report 382, pp 24, November 2006

Therefore development of a sustainable method of hydrogen generation would give a significant reduction in overall greenhouse emissions.

4.1.7 Conclusions

Nanotechnology is likely to be an enabling technology in the development of a hydrogen economy, with hydrogen fuel cells most likely to be utilised in transport applications. The major barriers to the development of the hydrogen economy are:

- **The development of an effective hydrogen storage medium**. This is the principal barrier preventing the development of a user friendly hydrogen powered vehicle. The likely solutions will probably involve the use of nanotechnologies, either as a method to maximise storage or in the development of hydrogen sponge materials.
- **The overall cost of the system**. The current experimental nature of the vehicles prevents meaningful comparisons between mass produced internal combustion engines and hydrogen fuel cells. However nanotechnology is addressing cost issues by reducing the use of precious metals and developing new nanoporous membranes.
- **Lack of infrastructure.** This can be addressed through public funding of demonstration projects to encourage the deployment of refuelling stations throughout the UK.

Nanotechnology is likely to be a cornerstone technology in the development of the hydrogen economy and will play a significant role in addressing the barriers outlined above.

Hydrogen may replace hydrocarbons as the main fuel source in road transport. However even the most optimistic projections suggest that it is unlikely that hydrogen will make any significant impact on private sector transport before 2030. Therefore the environmental benefit from using this technology, although large, will take a significant time period to realise.

The use of hydrogen fuel cells for stationary applications is likely to remain a niche application for the foreseeable future. There appears to be little requirement for using any energy store to smooth out intermittency of supply whilst the renewable energy component of UK electricity generation is less than 20 % of UK generation.[a] Further into the future, the economics of hydrogen as an energy store may become more attractive as the UK's energy mix becomes more reliant on renewable energy sources. Therefore focus should be placed on the development of hydrogen as an energy source for transport applications. It is likely that innovation in this sector will propagate development of stationary hydrogen power sources.

[a] The Costs and Impacts of Intermittency, UK Energy Research Centre, 2006.

4.2 Fuel efficiency

4.2.1 Overview

Description

Nanotechnologies that are currently being developed which improve the fuel efficiency of conventional fossil-fuel engines and turbines generally fall into one of four categories:

- fuel additives to catalyse improved fuel efficiency and reduce emissions in road transportation
- tribological improvements to improve fuel efficiency within engines, usually relating to surface coatings or improvements in lubricating oil systems
- nanostructured ceramic coatings on components within gas turbines that allow increased temperatures, hence better fuel efficiencies
- improved catalytic converters that improve air quality or minimise the use of platinum group metals in achieving equivalent air quality (i.e. largely a resource efficiency or pollution abatement justification rather than carbon saving).

Hence the range of nanotechnologies within this area is diverse and the impact, time to market and probability of exploitation need to be considered separately for each type.

Benefits over current/other technology

Fuel additives: commercial systems for diesel fuel have been developed based on cerium oxide powders, for example, those commercialised by Oxonica Ltd. This latter system relies on delivering low parts per million (ppm) concentrations of the powder to the combustion chamber of diesel engines which catalyses a lower combustion temperature and cleaner burning. This has delivered 5-10% reductions in fuel consumption in UK trials, with claims of up to 14% in other tests. Associated with this have been similar reductions in exhaust pollution metrics, for example particulates. This is largely a 'drop in' replacement, although additive packages have had to be specifically developed to include the powders and there is the requirement to meter in the additive to the fuel (or indeed to an individual fuel tank), either at an oil company installation, a fuel distribution centre or a fleet operator's premises, depending on the nature of the customer.

There are competitive systems based on cerium salts such as the Rhodia 'EOLYS' system, which meters in a concentrate into the engine in order to improve emissions but does not claim to improve fuel efficiency. Another cerium-based system is marketed by CDT in the USA which cleans up diesel particulate traps by lowering the temperature of trap regeneration.

Most competing systems not based on ceria nanotechnology are largely detergent-based additives which improve engine efficiency by cleaning the injectors. These are commercially available from fuel additive suppliers such as Infineum and are sometimes marketed as branded products by the petroleum suppliers. There are also Pt/Pd systems under development, where the metals are recovered in the catalytic converter/filter.

Tribological improvements: improved lubricant additives are usually based on oil soluble metal carbonate colloids, which meet the criteria of nanoparticles, although many traditional classes of colloid fall into this size category. These carbonates are added to neutralise the acids generated in combustion and thereby minimise corrosion and improve engine performance, including fuel economy and emissions. Without such colloids it is claimed by additive manufacturers that engine life would be significantly shortened. Development of the colloid nanotechnology within the industry is driven jointly by increasing restrictions on sulphur, metals and phosphorus in fuels (which puts consequent pressure on the lubricant formulation) and on the desire for improved fuel efficiency and emissions performance.

Nanodetergents are commercially available, although continuing development work may lead to further improvements in performance. Industry estimates of the potential in this area are that up to a 5% improvement in performance might be possible.

Nanostructured coatings for turbines: the purpose of the nanostructures is usually to improve adherence and integrity of ceramic coatings on key components within gas turbines, particularly in aircraft. These coatings enable higher temperatures and hence higher efficiencies to be obtained within the turbine. Companies such as Rolls Royce, Turbine Surface Technologies (a Rolls Royce joint venture) and UK universities such as Loughborough and Oxford are researching coatings on engine components such as nozzle guide vanes (which guide the hot gas stream), aerofoils and gas seals. Generally, nanostructured coatings are in the advanced research or development phase, with a time to market of around one to five years depending on approval and certification requirements.

The target temperature increases made possible by these coatings are of the order of 10^{o}C in a system that might be operating around 600^{o}C. The efficiency gains and fuel savings attributable may be of the order of 0.2 - 0.6%, depending on which component(s) are addressed and the degree of success of the research. So long as these efficiency gains were translated into fuel savings for the whole aircraft, the UK impact on GHG emissions would be of the order of 0.1m - 0.2m tonnes per annum of CO_{2e}[a]. Similar percentage impacts would be expected worldwide due to the international nature of air travel and of the aero engine industry. There will also be savings from land-based turbine applications where these coatings are implemented, but these have not been estimated at present.

Catalytic converters: Nanotechnology has been used in catalytic converters in cars for some years in order to reduce the use of expensive platinum group metals and improve performance. The further use of nanotechnology is focusing on:

- Incremental improvements to further reduce platinum group metal use and improved performance of the metal component and refractory support.
- Substitution of platinum group metals with cheaper nanoscale materials. Similar nanoscale catalysts are also being developed for applications in the chemical industry to replace platinum group metals.

In the use in catalytic converters, nanotechnologies are being employed to improve emissions performance at lower cost, rather than improving fuel efficiency.

Table 7 provides a summary of the nanotechnologies which provide transport fuel efficiency savings.

[a] Based on 2005 GHG emissions calculated from use of fuels from UK "international bunkers", AEA Energy and Environment

Table 7: Summary of nanotechnologies which provide transport fuel efficiency savings

Application of nanotechnology in:	Impact	Total potential UK GHG impact (mtpa CO_{2e})[1]	Total other potential environmental benefits	Distance from market / risk
Fuel additives	5% diesel fuel savings, 5% particulate reduction	3.1	1,200 tpa particulate reduction, net of additive	Commercially available
Lubricant additives	2% total fuel savings	2.4		Some commercially available. Other applications 2-5 years
Turbine coatings	0.5% aircraft fuel savings	0.2	Large international spillover benefits	2-5 years
Catalytic converters	Meeting of emissions targets at lower cost	0.0	Lower metal abstraction and production impacts	Commercially available; more radical applications 2-5 years

Notes:
1. Impact figures are based on 2005 and 2004 actuals, rather than forecasted emissions at expected time of commercialisation. Based on Transport Statistics 2006, Dept. of Transport/National Statistics

4.2.2 Potential policy implications

Fuel and lubricant additives are near or at-market solutions that can deliver small but globally significant carbon savings and emissions reductions through use in conventional engine systems without modification. We estimate that nanotechnology can deliver 7 % improvement in fuel consumption and pollution emissions across the two applications with greatest improvements in diesel engine fuel consumption and emissions.

Given the concerns of climate change due to fossil fuel consumption and threats to public health from particulate emissions from road transport, there is a justification for government intervention for the common good.

This could take the form of accelerating health and safety research, combined with support for validation trials.

Given that this technology is currently available, it is possible to estimate its implementation cost. This is approximately £20-£80 per tonne of carbon dioxide[a] and therefore compares favourably with Defra's figure of the social cost of carbon at around £70 per tonne. It also compares favourably with the cost of using bio-diesel estimated to give a carbon cost of £140 per tonne of carbon dioxide.[b]

A key issue will be the trade off (if any) between support for such modest near market developments and support for longer term more radical changes that will deliver much greater environmental benefit, but will require greater system changes in order to achieve them. Supporting solely such near market solutions may simply reinforce the current fossil fuel based technology unless funding for alternative, more resource efficient technologies is provided at the same time.

Nanocoatings for turbines is a much less contentious area in which conventional R&D support aids the development of advanced coatings. We estimate that nanotechnology based coatings and surface treatments are likely to improve turbine efficiencies by about 0.5% after fuller development. However potential risks are much lower and, because of the primacy of specification and approval procedures, government policy has much less capacity for influence. We propose therefore that there are no special policy issues of contention to be raised.

4.2.3 Route to market

Fuel additives are generally designed as a 'drop in' replacement so that no alteration of the diesel engine settings is required. Therefore the system changes required are fairly minimal, being limited to a dosing device that is required to meter in the additive, which is generally dispersed into a concentrate solution. The additive may be dispensed at a number of alternative points along the supply chain, from the oil company supplying bulk diesel deliveries through fuel distributors to fleet operators and individual car, van or truck owners.

The main technological barrier to overcome is the ability to provide comparable data for organisations interested in introducing the additive. Fuel consumption varies according to weather, engine type and condition, loading, etc. Although some trials have been carried out on, for example,

[a] Personal communication, Oxonica, 2007

[b] A letter to the committee chairman from Mr John Healy MP, Economic Secretary, HM Treasury, Environment, food and rural affairs select committee, 2003

two bus fleets, most organisations are unwilling to trust this data and wish to carry out their own trials. Providing convincing data from these trials is reported as being difficult.

Nanostructured turbine coatings are a refined version of continuing research work on surface coatings that help increase fuel efficiency and improve corrosion resistance. They are therefore not a radically different technology to what is in place at present, but a refinement thereof. Routes to market will depend on the demonstration of improved performance in conventional turbine systems, followed by a customer specification and approvals procedure so that these coatings may be used on commercial and defence aircraft and in static turbine systems.

4.2.4 Barriers to market

Fuel additives have an obvious potential risk from the exposure to air-dispersed nanoparticles of ceria. These risks need to be offset against the reduction in carbon particulate (which has a better known public health risk) that results from the use of the fuel additives. Using data from trials of Oxonica materials, the potential for carbon particulate reduction is around 1300 tonnes per year, compared to an introduction into the atmosphere of around 100 tonnes of cerium oxide nanoparticles. A BASF eco-efficiency analysis carried out on these materials concluded that even in a worst case scenario additised diesel outperforms unadditised fuel in Toxicity Potential. The latter, due to the significantly higher fuel consumption, results in greater particulate emissions (soot) as well as NMVOC (non-methane volatile organic solvents) and carbon monoxide.

Risks from lubricant additives are generally contained within the engine and are likely to remain entrained in the lubricating oil.

The ease and speed of introduction of new types of turbine components will be governed by industry specifications and approvals.

4.2.5 Recommendations

The potential for immediate short term gains in efficiency means that the government should consider:

- research into the effects of free airborne nanoparticles on human health and the comparison with better known hazards such as carbon particles from transport emissions
- support for a major demonstration project on fuel additives.

Such government support is justified on the basis of the social good of the particulate and carbon dioxide reduction possible using this technology and its modest cost implementation compared to other interventions.

It is important that such support should not be to the detriment of longer term nanotechnology research with greater environmental potential in case the government's actions simply help to 'lock in' conventional fossil fuel based systems through reducing costs without seeking longer term solutions.

For nanostructured coatings and catalytic converters we recommend the general continuation of the innovation related funding that is currently supporting this type of research and development, viz EPSRC materials and advanced engineering programmes, and the DTI Technology Programme.

4.2.6 Conclusions

These nanotechnologies are close to full scale production and commercialisation. The fuel additive offers a 'drop-in' solution which requires very little modification of the current infrastructure. The large aerospace industry in the UK is positioned to exploit any new technologies through university level research.

In the correct market environment, a measurable reduction in the UK's emissions could be realised. The technological barriers to market are relatively small however, in the case of fuel additives, health and safety concerns must be allayed. These could be addressed through independently funded safety and efficiency trials.

4.3 Photovoltaics

4.3.1 Overview

Photovoltaic technologies offer a potentially unlimited source of emission free, renewable energy by converting sunlight into electricity. The development of this alternative energy source is dependent on the availability of the energy generator and primarily solar radiation. This is clearly dependant on location and weather conditions. More favourable sites, such as Saharan Africa, can provide approximately 2,300KWh/m^2 of energy per year, whereas, in the UK, the higher latitudes and less accommodating weather conditions result in practical levels possibly as low as 800KWh/m^2 of energy per year. Based on current state of the art solar cells, this equates to approximately 20-30m^2 of solar cell required to power the average household.

In the UK, due to the relatively low energy yield from solar radiation, photovoltaics are likely to be utilised in distributed networks (mainly on residential and commercial roofs) or in remote off-grid systems (where an electricity infrastructure is unavailable), rather than as large 'solar farms'. To illustrate, current state-of-art solar cells require about 65 million m^2 (65 square kilometres) of photovoltaic cells to generate 1GW of energy, so even a generation rate in the UK of 5% from photovoltaic sources (i.e. 3.5GW) will require a photovoltaic cell area of over 225 square kilometres. Such an area (and consequent planning permission) would be difficult to obtain particularly in the more densely populated areas of the UK. Smaller units may be acceptable and could be created by using "set aside" farm land. The farming community have been made aware of this opportunity and one estimate puts the value of land suitable for photovoltaic farming as high as $60 million per square kilometre.[a] However, the majority of the future installed capacity is likely to be from rooftop microgenerators either on private residential dwellings or light commercial buildings.

The current photovoltaics sector is dominated by silicon solar cells, which command approximately 97% of the market. Silicon technology can be broken down into mono and multicrystalline silicon and thin film technologies. Data suggest that about 58% of the silicon market is held by multi-crystalline silicon (Table 8).

Table 8: Share of PV energy generation by technology (Source EU 2005)

PV Type	Multi-crystalline Si	Mono-crystalline Si	Thin films	Other
%	58	32	7	3

[a] http://www.carbonfree.co.uk

The current achievable energy conversion efficiencies using amorphous or multi-crystalline silicon are limited to less than 10%, compared with about 15% of theoretical maximum for monocrystalline silicon; this is due to amorphous silicon being about 300 times less active than the crystalline counterpart, but it has the major advantage of being significantly cheaper and more readily available.

A potentially better metric than overall efficiency of a solar cell is to examine the cost of electricity generation. Currently, for the best suited sites, photovoltaic power generation, costs approximately €4-5/W. Current estimates suggest that these costs can be reduced to €3.5/W by 2010 and €2/W by 2020, with a further decrease to about €1/W by 2030, but all these predictions are based on the assumption that major breakthroughs will occur in photovoltaic technologies. It is also assumed that energy conversion efficiencies will increase to between 30% and 50% after 2030. These major breakthroughs are, in part, predicted to emerge from the incorporation of nanotechnology.

There are major issues in the manufacture of silicon based solar photovoltaic cells. They are produced by sawing 0.2-0.3mm thick wafers from silicon. The process is very inefficient and generates about 50% waste. This low rate of manufacture is due, at least in part, to the material brittleness of silicon. Furthermore, since the photovoltaic cell comprises a brittle material, it becomes very susceptible to further damage and subsequent operating failure.

Other major problems with silicon based photovoltaic cells are their availability and price; when using conventional technology a medium sized silicon wafer factory producing 30cm wafers can manufacture only about 88,000m^2 per annum. Also the energy 'payback' time[a] for such manufacturing techniques is approximately four years.[b]

[a] The amount of time a solar cell requires to generate the same amount of energy required to manufacture it.

[b] net energy analysis for sustainable energy production from silicon based solar cells, Proceedings of Solar 2002 Sunrise on the Reliable Energy Economy, 2002

4.3.2 Nanotechnology approaches to developing photovoltaic systems

There are a wide range of different nanotechnologies with the promise to deliver either increased efficiencies or reductions in manufacturing cost. Below is a brief description of the various approaches, further information on these potential approaches can be found in Appendix 5.

- **Nanoparticle silicon systems**. It is hoped that by using nanoparticles of silicon the manufacturing costs can be reduced and (due to increases in surface area) the overall efficiency of the solar cell can be improved. However there are problems with the nanoparticles oxidising which limits the efficiency of the devices. New encapsulation technologies are required to abate this problem. Also the cost of silicon is a significant portion (approximately 40%) of the overall cost.

- **Mimicking photosynthesis**. The Grätzel cell uses nanoparticles of titanium dioxide (TiO_2) with an organic dye. Solar cells based on this technology are now in production. Current Grätzel cells are less efficient than silicon but are also considerably cheaper.

- **Nanoparticle encapsulation in polymers**. Inorganic nanocrystals which harvest light entrapped in a conducting polymer matrix efficiently could potentially reduce manufacturing costs. There is also the opportunity of using Buckminster fullerene to improve efficiencies. By altering the size and composition of the nanoparticles, the efficiency of the photovoltaic can be adjusted. However there are problems with encapsulation and integration of these technologies into working prototypes.

- **Calcopyrites**. These non-silicon materials are currently being produced as thin film photovoltaics. To reduce waste and decrease cost, the current research trend is to develop ever thinner layers of these materials. Forecasts suggest that these materials will begin to find use in mainstream applications within the next five years. One of the major problems with this technology is that this group of chemicals uses cadmium, which is a toxic metal. By layering two types of calcopyrites thin films (100nm) hybrid photovoltaics can be synthesised which are less susceptible to impurities and can be manufactured at lower temperatures.

- **Molecular organic solar cells**. Early stage research into molecular engineering is being conducted to develop molecular photovoltaic devices. This technology is still largely in the realms of synthetic chemists and is some way from commercial exploitation.

- **Organic polymer photovoltaic systems.** The use of nanometre layers of semi-conducting polymer has shown promise for low cost solar cells.

- **Single walled nanotubes in conducting polymer solar cells**. The addition of single walled nanotubes to conducting polymers shows promise in improving the efficiency of the conduction polymer.

- **III-V nitride solar cells**. The reduction of the particle sizes (or thin films) of III-V nitride semiconductors can result in highly efficient photovoltaic systems. The development of good manufacturing techniques and encapsulation technology is essential to these systems.

- **Flexible film technology**. A thin sheet of polymer can be coated in photovoltaic nanoparticles to create what is essentially a flexible solar cell. These flexible film solar cells could potentially be extremely cheap to produce (orders of magnitude cheaper than silicon cells). A major obstacle to the development of these systems is the development of a coating technology which provides flexible adhesion of the nanoparticles to the plastic film. Techniques such as inkjet printing or roll-to-roll printing may provide a high throughput solution.

- **Novel nanostuctured materials**. Nanomaterials are being used in a variety of other methods to improve efficiency. These are described in Appendix 5

4.3.3 Route to market

The use of nanotechnology in photovoltaics is in varying stages of development. In Europe, nanotechnology, which is seen as a potential route to reduce the cost / increase performance of photovoltaics, has not yet been fully exploited commercially and the required synergy between nanotechnology and the photovoltaics industry has not been developed. One of the major problems is that research into commercial photovoltaic technology is independent to developments in nanotechnology photovoltaic systems at the frontiers of science. Their current requirements for technological advances are slightly different. The fundamental science of nanotechnology-enabled photovoltaics is yet to be proven and work at this level is imperative. Capital investment needed in nanotechnology development by the photovoltaic sector is very high. Consequently, the photovoltaic industry is being developed by current fabricators in the sector, which is mainly non-nano. Conversely, nanotechnology-enabled photovoltaics are being developed by specialists in nanotechnology, such as SMEs and universities.

4.3.4 Barriers to market

Political

The major issue in adoption of all photovoltaics is in the cost. This is obviously due in part due to the cost of production and the expense of raw materials, but in addition, the UK taxation regime mitigates against the general public purchasing and installing of microgeneration systems such as rooftop solar cells, which are ultimately likely to make up the vast majority of installed photovoltaic capacity in the UK. For example, although the end user wishing to purchase photovoltaics cannot reclaim VAT on the purchase price, large scale energy generators are able to do so. The levelling of the tax playing field by offering similar incentives to the general public will encourage the installation of distributed renewable energy technologies. Tax incentives can have a measurable positive effect on the installed photovoltaic capacity; for example, tax incentives in Germany have led to 250,000 installations, whilst there are only 2,500 installations in the UK.[a]

Since the integration of nanotechnology with photovoltaic technologies is new and largely unproven there is a requirement for further work on fundamental understanding and commercialisation in the medium and long term.

The development of nanotechnology in renewable energy generation is uncertain and at the forefront of current research. There is therefore significant risk involved in any investments. Although the private sector could be left to develop the technology, the support of large scale projects such as clean rooms will help accelerate development. A Class 10 Clean room could, for example, cost as much as $1bn to build and such investment is unlikely for a speculative technology such as nanoparticle photovoltaics.

There is a high demand for rapid commercialisation by investing companies and this inhibits process and product development by preventing exchanges of ideas and information.

Social

The environmental and health concerns of nanotechnology are less pressing within this sector because the technology will be encapsulated within a benign material. Indeed, from a performance perspective, the encapsulation of the nanotechnology is one of the key goals of current

[a] Source: EEC.

research. Obviously, careful design and protocols for manufacture and controlling disposal at the end of the life of the device are imperative.

Technical

Efficiency:

The majority of research by photovoltaic industries is in the development of conventional photovoltaic cells using silicon. However opinion suggests that the efficiencies of silicon based cells are reaching their limit (10-15%) and new systems need to be developed to make any substantial gain.

Most current commercial, or close to commercialisation, nanoparticulate photovoltaics are less efficient than conventional silicon cells. This is possibly due to degradation of the nanomaterial and may be resolved by improving the encapsulation processes.

Price:

The desired objective is to create photovoltaic systems that can produce energy at less than $1/W. Generation costs of about $4/W are feasible using current technology. By increasing cell efficiencies from 10-15% to 50-60% through using nanoparticle technologies, such a price could be achieved, which is very ambitious.

However a more promising approach to the $1/W generation target is by the potential reduction in costs through novel manufacturing technologies and materials. This may be achieved by developing non-clean room processes combined with advances in technologies such as roll-to-roll printing.

Materials:

Currently, about 50% of the UK funding for R&D in photovoltaics is directed towards nanocrystals for nano-enabled systems. However, some of the more promising materials, including photovoltaic polymers, have yet to equal predictions about performance and may never fully realise their potential.

Once manufactured, nanoparticle photovoltaics will need protection from degradation; there is evidence that with current technology, the photovoltaics are very susceptible to oxidation and photo degradation. This reduces their life expectancy as well as their efficiency, so development work will be required in incorporating nanomaterials into “real world” appliances under “real world” conditions where they will have to operate for many years and even decades with minimal maintenance.

Funding

Most of nanotechnology research is being carried out in universities, who do not usually have the skills or capacity to develop the concepts further into products. On the other hand, venture capitalists show little interest in such high risk technologies when in their infancy. Finally, development by SMEs requires significant capital investment and development cost, neither of which is available because of the high risk factors.

4.3.5 Potential Policy Implications

If low cost photovoltaics can be developed and higher energy efficiency standards can be achieved these could encourage home builders to incorporate renewable microgeneration devices into new builds.

The foreign political landscape may change if large scale solar farms become viable. International political alliances with equatorial countries could lead to a shift in power in the world energy markets. This could benefit both western society, by moving reliance away from OPEC for energy and historically poor countries situated around the equator. Europe's Mediterranean countries, such as Spain and Greece, could also benefit.

4.3.6 Recommendations

To achieve the successful development of this technology, the following recommendations are made:

Current exploitation of nanotechnology and photovoltaic technologies are limited by a lack of adequate expertise in their technology development. Universities are carrying out fundamental studies but are not positioned to develop the commercial technologies. Spin-out companies, on the other hand, are well positioned to develop the technology and exploit its advantages, but are unable to acquire the high capital funding needed since suitable funding sources such as venture capitalists are more interested in shorter term projects. Consequently, successful process development and exploitation should be funded by central Government;

To maximise effort and minimise duplication of concurrent developments, there should be the establishment of a "Centre of Excellence" for the generation and storage of renewable energy. This will facilitate co-ordination with other similar European centres, thereby minimising costs to the EU. Existing initiatives such as:

- MNT initiatives and centres
- energy technology institutes
- national renewable energy centre

could provide this service. There may be a role for these technologies in the upcoming DTI funded energy technologies institute. Alternatively NAREC (the new and renewable energy centre) could be expanded to address some of the shortcomings of the sector.

Specific areas of development should be focussed on:

- high efficiency, non silicon systems based on materials such as calcopyrites, semi conductor hybrids and group III-V systems;
- flexible substrates
- nanoparticle encapsulation
- photosynthesis replicating systems
- manufacturing processes
- manufacturing cost reductions
- co-ordinated high efficiency energy storage systems
- solar radiation concentrators.

The use of public purchasing should be considered to stimulate development in high efficiency end-use products that will benefit from stand alone photovoltaic systems. Such products might include street signage, lighting and similar products. This will allow significant use of unobtrusive and free standing generating units, and would stimulate other 'strategic niches' that would help the further deployment of the technology and the development of the industry.

The current tax regime should be revised to give microgeneration systems similar tax breaks to those offered to energy generators when building large scale generation facilities.[a,b]

A requirement for the incorporation of photovoltaics into new housing stock should be set. This will stimulate growth in the sector and create a favourable environment for developments in new photovoltaic technology.

The majority of the discoveries surrounding photovoltaics and nanotechnology have stemmed from fundamental research. Continued support for this research is imperative to further the science.

[a] Unlocking the power house: policy and system change for domestic micro-generation in the UK. http://www.sussex.ac.uk/spru/documents/unlocking_the_power_house_report.pdf
[b] In a recent development the Chancellor announced the government would engage the EU to allow a reduced VAT rate on energy saving products.

4.3.7 Potential environmental impact

The Energy Saving Trust has estimated that PV could contribute 2.7% of our domestic generation by 2050. This equates to 5.4 Mte of CO_2 per year. It is not possible to estimate the contribution of nanotechnology to this figure; however, for these figures to be met, significant efficiency gains and cost reductions must first be achieved. It is likely that nanotechnology will help drive this transformation. Also, it important to note that there will be additional emissions from the production of the solar cells; however this cannot be measured accurately due to the early stages of the technology development. It is also important to note that the technologies outlined here could potentially reduce the overall energy consumption for the production of solar cells, which, using current methods of silicon production , have a significant 'pay back' period.[a]

4.3.8 Conclusions

There are a large number of fundamental research projects investigating the use of nanotechnology in solar cells. The main application of solar electricity generation in the UK is likely to be in the form of distributed networks on the roofs of residential buildings and light industry. The major barrier to their implementation is the total cost and payback time. This is largely due to the cost of silicon, which can constitute approximately half the cost of the unit. The development of thin films and other nano-enabled devices is likely to reduce the overall cost making photovoltaics more financially attractive.

The successful development of new photovoltaics systems requires a variety of different scientific and engineering disciplines. There is a need for a facility where researchers with different specialisations can interact and work on the same project. Also, due to the complexity and long development time of the product, there is a need for funding for early stage, post pure and applied research to enable commercialisation.

[a] http://www.energybulletin.net/17219.html

4.4 Batteries

4.4.1 Overview

Batteries[a] are the main form of energy storage for mobile applications. At the top of the consumer portable information and communication technology (ICT) 'wish list' is longer lasting batteries for mobile devices. This demand has driven improvements in efficiency and storage capacity. Before this, for example, the most recent jump in performance of batteries was the introduction of the rechargeable Li-ion cell by Sony in 1990.

Electric powered transportation has been, until recently, restricted to use in trains, trams and trolley buses where electricity can be supplied either through a cable or track. Electric powered personal transportation, namely electric cars, is perceived as expensive, low powered and having long recharge times and an impractically short range. The central reasons for this are that the evolution of battery capacity, namely the energy density, has increased by only 65% in seven years, whilst semiconductor performance has improved by 2600% over the same period. Unlike other high technology industries where a doubling in performance is seen as normal, this type of gain would be considered revolutionary in the battery industry. The slow pace of improvement in battery technology has probably resulted in the intense activities in developing fuel cells for both ICT and transport applications.

A current practical solution which uses batteries to power cars is the hybrid vehicle such as the Toyota Prius or the Lexus RX 400h. These combine traditional internal combustion engines with batteries and electric motors. At low speeds and in city traffic the cars use electric power to drive the car, which is considerably more efficient than a petrol engine. At higher speeds (such as motorway driving) the petrol engine provides power. The car's batteries are recharged by a petrol driven generator. This system can reduce overall petrol consumption by up to 37%. Such a system also removes the issue of limited range associated with a battery powered car

[a] Batteries are devices which store electrical energy in chemicals. There are several different chemical reactions which can occur within the battery but all batteries share the same basic design. Batteries have two electrodes connected to a circuit, a chemical reaction at one electrode generates electrons, whilst a chemical reaction at the other electrode consumes electrons. These two parallel reactions generate a current of electrons (electricity) through a circuit. A battery is recharged by the reaction occurring in reverse using an external current to push electrons in the reverse direction. The chemical composition at the electrodes determines the strength of the electric current and the capacity of the battery. The chemicals are usually metals salts, such as nickel, lead and lithium and the electrodes are usually elemental metals.

and the infrastructure is well established to recharge the battery using petrol. Hybrid vans and buses are also in development and operate under similar principles to hybrid cars.

Ultimately, the use of fossil fuels as an energy source for transportation must be minimised (if not removed) in order to reduce the UK's environmental burden. The hybrid car will probably only be considered a stop gap in the pursuit of zero emissions from private transport. In addition to fuel cells (see Section 4.1) battery powered vehicles have the potential to deliver zero emissions for transport. Electric vehicles have a long history but have, until recently, not been considered competitive in performance (notably range) compared with liquid fuelled vehicles. Currently, intense development has resulted in the launch of a limited range of electric vehicles. There is, for example, an electric powered van. However, with a range of 60 miles, this only appears to be suitable for niche applications. The problem of range seems to limit battery powered vehicles to niche areas of private transport in the near term.

Unlike the hydrogen equivalent, electric cars can utilise the current electricity distribution grid to refuel. Such cars could essentially be charged via a standard plug at home. However, away from the home, the lack of infrastructure for charging up an electric vehicle will limit journeys to within the vehicle's range. With current charge times of around eight hours, stopping at a refuelling station is impractical.

Current hybrid vehicles, such as the Toyota Prius, use nickel metal hydride power cells. However, Li-ion batteries are regarded as being more suitable candidates for hybrid or electric vehicles. They have the highest charge density of all common rechargeable batteries. The portable consumer ICT market has been the catalyst in developing these batteries. The battery typically comprises a lithium cobalt and a lithium carbon electrode. Chemically, lithium is the ideal element in the periodic table to produce high powered batteries. Li-ion batteries now account for 55 % (excluding lead acid) of world sales of rechargeable batteries (mainly in the portable electronic sector). However, if the battery is pierced, the lithium reacts violently with water possibly leading to fire and explosion. A lithium battery can also become unstable and may explode if it is overcharged or rapidly discharged. For these reasons a typical Li-ion battery can contain up to six separate safety features, which adds weight and expense to the unit. The dangers of using Li-ion batteries were recently highlighted when certain Dell laptops spontaneously combusted,[a] leading to the recall of 4 million Li-ion batteries by Sony. Attempts to increase the power density of these batteries whilst increasing their safety have focused on combining

[a] BBC news

lithium with other elements such as sulfur. For these reasons, the current generation of hybrid vehicles use nickel metal hydride.

A further technical issue, other than range, limiting the viability of electric cars is the charge time. Currently, the speed at which a Li-ion battery can be charged is restricted, usually taking several hours. This is less of a barrier for consumer electronic goods or depot based vehicles (such as milk floats or golf buggies), however a four hour wait to charge an electric vehicle is impractical if it has to be performed at a refuelling station. Realistically, for convenience, battery powered cars need a recharge time of less than ten minutes. This is comparable to the refuelling time for a petrol engine. The long recharge time is also a problem for regenerative braking.[a] In hybrid and electric vehicles regenerative breaking results in recharging occurring at very high power rates over short periods. This power surge is too high for Li-ion batteries, and therefore it cannot be fully exploited.

The problems of range and power are being addressed. For example the Tesla Roadster fully electric sports car (due to be released in early 2008) has similar performance to a Porsche Boxster and has a range of 250 miles. However, its recharge time is still several hours. Nanotechnology is seen as a lead candidate to address this problem.

In a Li-ion battery, the recharge and discharge rate are limited by the rate of adsorption and desorption of lithium from the anode and cathode of the battery. An increase in surface area of the electrode will allow more lithium to absorb faster onto the surface of the electrode. Also, in theory, these systems can store greater charges because there is a larger surface area for the lithium to react with. Research on batteries involving nanotechnology is focused on developing nanostructured electrodes which provide a high surface area, are low cost, easy to produce and stable (to avoid reduction in battery performance over its lifetime).

In the USA, Altairnano have replaced the carbon graphite electrode of a standard Li-ion battery with a nanostructured lithium titanate spinel oxide (LTO) electrode. These electrodes are claimed to have a 100 times higher surface area than the standard graphite electrode speeding the recharge and discharge rate of the battery. The low reactivity of these materials reduces the reactions between the electrode and the electrolyte which can increase charging time. The low reactivity of the electrode also extends the lifetime of the battery and allows it to function in more extreme climates than conventional Li-ion batteries. However, the battery holds less charge than a conventional Li-ion battery. This battery system is being used by the Phoenix Motor Company (based in California) in an electric vehicle which

[a] Whilst the car is breaking the electric motor which powers the car operates in reverse pushing current back into the battery, which results in the battery recharging.

is due for limited release in 2007. Using a special adaptor the car can be charged in under ten minutes or overnight using conventional mains plugs. It also addresses part of the stigma associated with electric powered vehicles, as it is certified for use on freeways, has a top speed of 95 mph and a range of 130 miles. It is planned to extend this range to 250 miles by 2008.

Hence companies are claiming significant advances based on nanotechnologies in making electric cars competitive with liquid fuelled ones. These developments, if fully verified, are likely to be 5-10 years from introduction onto the mass market.

Qinetiq are collaborating with several major battery and automotive manufacturers to develop new batteries. The research is industrially sensitive but does involve using nanostructures to improve battery performance.

Researchers at the University of St Andrews are developing nanostructured materials which are able to hold more lithium than standard Li-ion battery electrodes. The development of these materials is likely to result in batteries with higher charge density.

Supercapacitors

Supercapacitors could provide a solution to improve the efficiency of regenerative breaking. Unlike batteries which store electricity using electrochemical potential, capacitors store electricity on two charged plates. Supercapacitors are capacitors that can store large quantities of electricity. Capacitors have traditionally been used to provide very short bursts of energy (usually less than one second). The amount of charge that they can store is limited and they are usually much larger and heavier than a battery of comparable power. With recent rises in storage capacity, supercapacitors have been proposed as a potential replacement to traditional batteries.[a] Capacitors have the advantage that they can be charged and discharged instantaneously and are therefore potential candidates for energy storage for regenerative breaking. The storage capacity of a capacitor is dictated by the surface area of its two charged plates; the higher the surface area the larger the capacitance. Using nanostructured surfaces the amount of charge a capacitor plate can hold can be significantly increased.

Researchers at MIT are developing supercapacitors with carbon nanotubes.[b] The researchers have developed a technique which attaches

[a] Electronics Weekly, 2004.
[b] www.mit.edu

one end of the nanotubes to a conducting plate. The material has a very high surface area and is being proposed as a potential supercapacitor.

Nanotecture, a spin off from Southampton University, is developing a technique which allows a multitude of nanostructured materials to be built. They have produced supercapacitors which out perform current commercial alternatives. The low environmental impact process used to produce the supercapacitors has received significant interest from the automotive sector for use in hybrid vehicles. The process can also be adapted to build nanoporous electrodes for batteries.

Stationary storage

With an increasing proportion of UK energy being generated by renewable methods, large stationary methods of energy storage are required to ensure that the UK has a reliable electricity supply. Regensys, a large scale poly sulphide flow battery, was trialled in the UK under the DTI technology programme and offered large storage capacity for intermittent electricity supply for renewable energy. For reasons discussed in Section 4.1, the cost of developing large scale electricity storage is unlikely to compete until the renewable energy mix exceeds 20 %.

4.4.2 Potential policy implications

The issues of end of life disposal of batteries should be given careful analysis. The materials used in battery production are toxic and an increase in production for use in vehicles could therefore have a negative environmental impact. The end of life vehicle directive requires 85 % of a car to be recycled. The incorporation of difficult to dispose of components (such as Li-ion batteries) is likely to increase the cost of disposal of hybrid or electric vehicles.

If supercapacitors surpass performance of batteries, the current batteries directive may need to be redrafted to incorporate supercapacitors.

4.4.3 Route to market

The introduction of hybrid cars is currently underway. Any breakthrough in battery and supercapacitor technology that allows a 'drop in' replacement of the current technology will be readily incorporated into new vehicles. The relatively recent and limited introduction of these vehicles suggests that price, performance and efficiencies are likely to improve. The current first generation of hybrid vehicles is petrol driven, largely to satisfy the Asian and American markets. The launch of diesel powered hybrids is expected to occur in early 2008, probably within Europe, where diesel has a higher market penetration. This launch is likely to result in fuel savings of around 25-30% over current diesel engines.

The lack of a large multinational automotive company headquartered in the UK limits to an extent the commercialisation of new developments from within the UK. However, due to the global nature of the automotive industry, any major developments in the UK should be quickly exploited by the global manufacturers.

The lack of infrastructure to recharge electric vehicles and the long charging times of the current generation of electric vehicles will restrict their use to commuting journeys. Without satisfactory reduction of the charging times electric vehicles may never reach mainstream use. Current electric car manufacturers concede this and generally see electric cars initially assuming the role of a second car, used mainly for short journeys or commuting known distances.

If the problems of charging times can be reduced, a network of charging stations will need to be developed. It is likely that these will be incorporated into the forecourts of traditional refuelling stations nationwide. The power to fast-charge a car will be too high for domestic use through a conventional socket, but may be possible to incorporate into a separate ring main. The development of a fast-charge infrastructure will obviously result in significant outlay in both capital charging equipment and upgrades to the electricity distribution network (the national grid). However, the ability to recharge the vehicle overnight will reduce the burden during peak hours.

4.4.4 Barriers to market

It is clear that without the development of rapid charge, high capacity batteries the use of electric vehicles will be limited to niche applications or for short defined journeys. Nanotechnology appears to be a front runner in allowing the battery with the highest charge density, Li-ion, to charge and discharge rapidly. Supercapacitors may provide a solution to improve power output during acceleration and to utilise fully regenerative breaking.

The incorporation of nanotechnology into batteries is occurring on the research scale. However, there are problems in developing the process for an industrial scale. Ultimately, the cost of hybrid or electric cars should be comparable to a conventional internal combustion engine car. This will partly be achieved through mass production. A key challenge will be the ability to generate nanomaterials on the scale required for mass production. Most methods for manufacturing nanoparticles are expensive, energy intensive and relatively low volume. The largest volume nanoparticulate production facilities at present use plasma technology to produce multi-tonne volumes.

Electric vehicles cost approximately one penny per mile. They are of simpler technical specification and therefore are claimed to be more reliable. The current road tax and congestion charge schemes provide favourable benefits for zero emission cars. The cost of running an electric car, therefore, is considerably less than a conventional car. However the initial purchase price of these vehicles is likely to be higher due to the low volume production runs, the experimental nature of the vehicles and the expensive and rare elements used in the battery construction.

The recent fall in oil prices has pushed down the price of petrol. In the USA, the high prices of fuel drove demand for hybrid vehicles. With the recent fall in fuel prices the sale of hybrid vehicles has also fallen. Higher overall petrol prices would force Americans to considered hybrid vehicles. In Europe (and in particular the UK) the very high petrol prices are seen as a market pull.

During our interviews, there was a feeling that support from both industry and government was missing or inadequate for medium to long term high technology projects, such as developing new battery technology. Perceptions were that attitudes towards long term high technology investments (in both the public and private sector) in the Far East and the USA were more forthcoming than in Europe. This problem is endemic throughout UK science and innovation and recommendations are stated elsewhere.[a] Also, funding where there are requirements for consortia is difficult to initiate in the UK due to the lack of a UK based automotive manufacturing base. The relatively low interest from EU car and battery manufacturers is forcing innovative nanotechnology companies to look in the USA and Asia for contracts. The physical distance inhibits growth in development in the UK.

There appears to be sufficient venture capital funding available for promising technology. High fuel prices and the development of congestion charging provide a strong market pull in the UK for the development of

[a] Lambert review of business-university collaboration, 2003

hybrid and electric vehicles. The major automotive and battery manufacturers are receptive to innovations; large scale deployment of new technology should be relatively straightforward, however this will have implications for infrastructure in the UK.

4.4.5 Potential environmental impact

The use of hybrid vehicles is still in its infancy. Looking at current overall energy savings, hybrid vehicles are approximately 15 % more efficient than similar petrol cars.[a] This would result in a potential saving of 10 Mte of emissions if applied throughout the UK fleet. The savings offered by nanotechnology are difficult to predict. Market transformation is also likely to take significant time given the current limited availability of hybrid cars and time for replacement of the UK's fleet (which would take at least 10 years).

Using the current USA energy mix, electric vehicles can give approximately a 65 %[b] saving in carbon dioxide emissions. Assuming similar efficiencies of electricity generation in the UK, a saving of approximately 42 Mte of carbon dioxide can be realised by adopting electric vehicles throughout the UK car fleet. It would also reduce city emissions to zero which would have a positive health benefit. As renewable energy increases its share of the UK's energy market the overall emissions from electric vehicles will reduce. Without the reduction in charge time afforded by nanotechnology, this saving in emissions is unlikely to be met. Until a reduction in charge times (potentially using nanotechnology) and infrastructural changes allow rapid-charging, the use of electric cars will remain niche. If these issues are resolved the electric car could replace petrol driven vehicles, which is likely to be the result of nanotechnology.

4.4.6 Recommendations

In the short to medium term the use of battery powered transport will be limited to light vehicles such as cars. Therefore efforts to encourage the uptake of these vehicles should be focused on the general public. Nanotechnology could potentially enable the development of viable battery powered and hybrid transport. The costs of these systems, however, are prohibitive to their wide scale adoption. Undoubtedly, these costs will decrease through economies of scale as more cars are produced. In the

[a] Using statistics from the 2006 US EPA fuel economy statistics Honda Accord: hybrid 31 mpg, Petrol 29 mpg; Honda Civic: hybrid 50 mpg, Petrol 34; Toyota Comry: hybrid 39 mpg, Petrol 28 mpg

[b] California environmental protection agency air resources board staff report: Initial statement of reasons for proposed rulemaking, public hearing to consider adoption of regulations to control greenhouse gas emissions from motor vehicles. 2004.

near term, due to the lack of recharging infrastructure and long recharge times, battery powered vehicles will be used for commuting and city driving. This is also where battery power can provide the largest benefits; petrol cars are inefficient in stop-start urban environments. To encourage this, fiscal incentives should be introduced or expanded, for example the congestion charge scheme for central London, with exemptions for electric and zero emission vehicles, could be extended to other high density urban areas.

The launch of electric vehicles needs to be combined with investment in fast charging networks. Such market deployment measures will require involvement of planning, health and safety, electricity companies, local authorities, architects, building service engineers, and a variety of other professionals and stakeholders. These issues will need to be raised nationally but engagement at a European level, to ensure standardisation, is important.

Procurement strategies should be employed for hybrid vehicles in the near term and electric vehicles in the medium term. In addition to government led environmental purchasing policy, large fleet operators should also be engaged. For example, large car hire firms or taxi companies should be engaged to incorporate a percentage of hybrid vehicles into their fleet.

The relatively short term approach to the development of new technologies should be addressed. The DTI Technology Programme has funding for preliminary, development and near market development projects. To develop a product from early stage research through to commercialisation using DTI funding the project must reapply for funding at several stages throughout its development. Funding calls can change during this time which can result in potentially highly innovative ideas being denied funding due to changes in focus. The reapplication process can also remove resources from the project. A potential solution to this is to give preferential funding to outstanding DTI projects which require follow-on funding, independent of the current DTI calls. The deliverables from one stage of the project would help assessors decide whether further funding was justified. This could also reduce the time required to reapply for further funding and decrease risk for potential partner companies because funding for outstanding projects would be more secure. This has the advantage that it will fit within the current framework of the DTI Technology Programme structure at the same time providing a route to develop innovative technologies rapidly. There was also criticism that the time between application and project initiation was too long. The upcoming DTI funded energies technology institute may provide this role.

From interviews, there is a need for further research into high throughput technologies for mass producing nanomaterials. Current methods are energy intensive and expensive, or use toxic precursors.

4.4.7 Conclusions

The use of batteries in cars to improve fuel efficiency is beginning to occur with hybrid vehicles. Nanotechnology has the potential to increase recharge and discharge speed of the batteries which would lead to improvements in efficiency of regenerative breaking and increase the power density of the batteries. For electric vehicles, nanotechnology could allow the utilisation of Li-ion batteries which would make electric cars more practical through increases in energy density. Supercapacitors, using nanotechnology, could increase the ability of an electric car to recover energy through regenerative breaking and could also be used as a buffer to store energy for use when a high power demand is placed on the battery (during fast acceleration, or up steep hills).

Nanotechnology innovations in batteries and cars are beginning to emerge (mainly in the USA and Japan). The cars are more expensive than conventional petrol driven vehicles and the payback (through fuel efficiency savings) are impractically high. To address this, the use of hybrid and electric vehicles can be encouraged through fiscal measures and environmental instruments such as the London congestion charge zone.

Large fleet procurement policies could be used to encourage the take up of hybrid vehicles and, in the medium term, electric vehicles.

Fully electric vehicles are likely to be used only in niche applications or for short distance commuting until issues surrounding charge time can be addressed, possibly using nanotechnology. If the charge times of electric vehicles can be reduced to an acceptable level (considered to be less than 10 minutes), there will be a need to build a fast charge infrastructure, which will require substantial governmental co-ordination activity.

4.5 Insulation

4.5.1 Overview

Thermal insulation is incorporated into buildings to reduce heat transfer. This is largely to prevent heat from within a building escaping, but in hotter summer months it is also beneficial to prevent external temperatures from increasing the internal temperature. To achieve this, products such as fibreglass, cellulose, wool and foams, which trap air in pockets between fibres have generally been used. There are three methods of heat transfer: conduction, convection and radiation. Mass insulation significantly reduces conduction and convection, but radiative heat loss is largely unaddressed.

There are several different ways of measuring the insulating properties of a material (e.g. concrete, fibreglass) and of a building element (e.g. roof, wall). Often the insulating property of a particular insulating material is expressed by its k or R value. The higher the R value and the lower the k value the better an insulator it is. The insulation property of a building element is usually expressed using its U value. The lower a material or building element's U-value the greater its insulation properties.[a] Typical values are given in Table 9.

Table 9: The insulation properties of some common building materials[b]

Material	k value (W/mK)
Mineral Wool (≤160kg/m^3)	0.030 – 0.044
Phenolic Foam	0.025
Glass	0.8 – 0.93

[a] The insulation properties of a material can be measured in several different ways. A materials thermal conductivity **k** can be considered, or a materials thermal resistance its **R** value, can be used. The insulation properties of a material or system can also be expressed using its thermal transmittance, the **U** value. This is a more complete measurement that takes into account losses through convection and radiation as well as conduction. The lower a material's U-value the greater its insulation properties.
[b] EST, CE71, Nov. 2005.

Table 10: Limiting U-value Standards for new residential dwellings as set out in L1A[a]

Building Element	Area Weighted U-value (W/m²K)
Roofs	0.35
Walls	0.25
Floors	0.25
Windows	2.2

New Buildings

Residential dwellings comprise a significant proportion of the building stock in the UK. Current building regulations covering thermal efficiency are shown in Table 10.

Such standards are readily achieved with current mass insulation products combined with good building practices. Some developers have already designed homes to meet higher standards, for example the EcoHomes standards used by the Little Alex Development in Hulme.[b] The new Code for Sustainable Homes supersedes the EcoHomes standards and comes into voluntary practice from 1 April 2007 and compulsory practice for publicly funded homes from April 2008, with privately funded new builds being encouraged to meet these targets.[c] Homes that meet this target will be required to be 10% more energy efficient than homes built to 2006 standards, with much encouragement to achieve higher improvements than this. It is likely that where these targets require improved insulation properties these can be met through the use of standard insulation products. There is no discussion in the public domain that new products are required to achieve these targets. Standard insulation products also appear to be sufficient to meet the requirements for insulation of hot water and heating systems.

Newly built commercial premises are now regulated to a similar level as residential dwellings and are required to satisfy Building Regulations L2A, which incorporate guidelines for acceptable U-values for building components[d]. The U-values for particular building elements are the same as those described in Table 10 above for new residential buildings, with additional criteria covering elements not normally found in a house, for example vehicle access and roof ventilators. Again current products

[a] The Building Regulations 2000, Conservation of fuel and power in new dwellings L1A.
[b] A Guide to EcoHomes, Hastoe Housing Association, www.sustainablehomes.co.uk
[c] Code for Sustainable Homes, from the DCLG, December 2006.
[d] The Building Regulations 2000, Conservation of fuel and power in new buildings other than dwellings L2A.

provide satisfactory insulation and there is little discussion that new products will be required to meet future regulations.

Existing Buildings

It is clear that current insulation technology is sufficient to satisfy current thermal insulation building legislation. An advanced 'nano-insulation' will be unlikely to compete due to the low cost of current insulation materials. Unless the legislative requirements for thermal insulation are raised, making current insulation methods inadequate, the use of novel insulation materials is likely to remain niche.

The majority of the country's residential building stock predates the requirement for cavity wall insulation. Much has been done to encourage people to increase the energy efficiency of their homes, with the installation of retrofit insulation being a key recommendation. However, of the possible 15 million homes that have cavity walls and could therefore benefit from installing cavity wall insulation, 10 million have not yet done so.[a] There is also a significant proportion of housing stock within this category that has little, or insufficient, loft insulation. Current products largely satisfy design and use requirements and the lack of take-up is not due to a lack of appropriate products.

Extensions to existing residential dwellings almost always require adherence to Building Regulations and these require insulation to be fitted to meet the same criteria as for new builds. Again, current products appear sufficient.

Over a third of the UK housing stock - 8.8 million homes - consists of non-cavity wall construction buildings: solid brick, solid stone, pre-1944 timber frame and concrete construction.[b] Such buildings may be able to install loft insulation but additional insulation to walls presents a more significant challenge. The current advice is to insulate the walls externally or internally. Internal insulation involves either dry lining the walls with flexible thermal linings (10mm thick), applying laminated insulating plasterboard (generally in excess of 60mm) or erecting a studwork fame and filling the created cavity with fibrous insulation. External insulation involves the application of an insulation layer fixed to the exterior of the wall, with a protective render or decorative cladding over the top. While both of these solutions offer significant improvements in terms of thermal efficiency, neither is financially practical unless a significant renovation is being undertaken at the same time. Also, both methods involve completely covering up the original building materials which will be prohibited in

[a] Figures from National Insulation Association.
[b] National Insulation Association, Householder advice.

many period buildings and may not be a desirable option for many other home owners. Consequently there is a significant gap in the insulation market where high-tech coatings, potentially making good use of nanotechnology, could be developed to address this need.

There is much existing commercial space, the energy efficiency of which could be dramatically increased by use of improved insulation, for example buildings used purely or largely as office space.[a] The rate at which improvements in energy efficiency are occurring in this area is reported as slow.[b] Many of the issues that exist for residential dwellings also exist for commercial premises. For example many premises lack cavity wall insulation and adequate loft insulation, although there is less data available for such conclusions than for residential dwellings. Any improvement to the rate at which such premises adopt improved insulation measures would be beneficial. However a dramatic improvement could be achieved with standard products. In terms of commercial premises with solid wall construction the same issues as with solid wall homes arise, and this is an area where there is a significant gap in the insulation market.

Current Insulation Products

Alongside the traditional mass insulation products, such as glass fibre, wool and cellulose, many new products are coming onto the market. Companies are exploring ways to improve the insulation properties of currently available products; for example BASF has produced a micro-layered insulation product with an inserted metal layer that provides radiative insulation (as well as the usual conductive and convective) and hence delivers an increased level of insulation.[c] Recent developments also include novel coatings for walls that are designed to reduce heat losses. For example a product that might go some way to alleviating the absence of insulation, so preventing the escape of radiation transferred heat loss, is a novel coating additive called Thermilate, which incorporates microspheres into a normal paint system. It claims to reduce the amount of heat the walls and ceilings absorb through the creation of a thermal barrier.[d] This product does not make use of nanotechnology, but of micro technology, and independent verification of its claims has not been obtained.

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[a] 13th April 2006, Submission by the National Insulation Association to the 2006, UK Energy Review

[b] National Insulation Association comment.

[c] BASF communication.

[d] Thermilate website: http://www.thermilate.com/

Current Products incorporating Nanotechnology

There are few current novel products claiming to incorporate nanotechnology. Those that are already on the market include Nanogels, a range of silica aerogel products produced by Cabot Aerogel to deliver increased insulation performance for oil and gas extraction and processing sites.[a] A range of aerogel products for the same market has been released by Aspen Aerogels.[b] Such materials are now being marketed in the residential dwellings sector for use in situations where diffuse light and high insulation properties would be beneficial, for example conservatory ceilings and skylights, and in areas where space is very limited and mass insulation is inappropriate. However such applications are relatively niche and these products do not appear to be replacements for mass insulation. The cost of such applications will remain prohibitive until the environmental implications are assessed. There is also a range of water based coatings; the Nansulate range of products from Nanotech Ltd which are designed to be applied to residential buildings on walls, metallic and wood surfaces and exterior walls and claim to significantly reduce heat transfer. Such a range of products may begin to address the market gap of insulation appropriate for solid wall buildings, but there is little independent verification of the efficiency of these products so far.

Several standard products used throughout the building industry have been identified as already making use of nano-level processes. However, the industry chooses not to emphasise this as the technology is not considered to be 'nanotechnology'. One reason cited was to avoid potential health, safety and environmental concerns from their customers. One example is Knauf glass fibre which, during its manufacture, has a silane bonding agent at a nano-level thickness applied to its surface as it leaves the melt. This promotes adhesion between the glass surface and the binder, helping the manufacturing process but also helping to prevent the fibres sticking together during their lifetime, which would lead to a reduction in their insulative properties.[c] Similar level processes are used by Rockwool in some of their insulation products.[d]

Another standard product that has nano-level processes incorporated into it is Pilkington glass.[e] Pilkington, a major manufacturer of glass for the construction sector, commonly uses a wide variety of thin-film coatings on the inner surface of its double glazed panels. Low E glazing is used to reduce the heat lost from the cold window surface by incorporating a metal

[a] Cabot Aerogel website: www.cabot-corp.com/nanogel
[b] Aspen Aerogel website: http://www.aerogel.com/
[c] Comment from Dr. C. Johnston, Oxford University.
[d] Communication with Rockwool.
[e] Information from Pilkington

coating into the window unit which reduces radiative heat loss. A typical Pilkington low E product has a coating thickness of around 75nm, while some of the more sophisticated coatings, many of which are designed to reduce heat transfer, are around 250nm thick. Using Optitherm™ low E glass into an IGU (insulated glass unit) allows U-values of 1.1 - 1.2 to be achieved, twice as efficient as required by Building Regulations Part L. Other glazing companies are known to use nano-scale coatings on their products as well.[a] Both of these processes may be described as using nanotechnology in insulation, and both already deliver environmental benefits.

Future products incorporating nanotechnology

There is a great deal of discussion and theorising concerning the use of nanotechnology in insulation from many different sectors. However products which exploit nanotechnology, either in the development stages or nearing market release, are very limited.

Companies such as Bayer and BASF are developing products for the insulation market that make use of nano-scale concepts.[b] BASF, in addition to its current foam insulators, Styrodur® and Neopor® is developing an insulation foam with nano-dimensional pores of around 100nm to be called Nanopor.[c,d] BASF states that conventional foams use only 50% of their thermal insulation potential, so a reduction in pore size will likely bring an insulation benefit. However such a product may only exploit a portion of the possible 50% energy saving. This product would be suitable for a number of applications, including use in cars, refrigerators and buildings, but it would be created from a reduction in foam particle size rather than from a new breakthrough technology being developed

Vacuum Insulating Panels (VIPs) are a developing area that is often discussed in connection with developments in nanotechnology. VIPs are composed of a core material surrounded by a thin barrier designed to hold a vacuum for extended periods of time. Once the system is fully encapsulated it is evacuated and sealed. Thus the gas molecules that would normally transfer heat are not present, so a superior insulator is produced. INSTILL from Dow Chemical Company is one such current system that makes use of micro-level technology and provides 3 – 7 times

[a] DTI, NANOMAT: Nanomaterials manufacture and applications – a mission to Finland, Germany and Switzerland, April 2005.
[b] BASF Products Utilising Nanotechnology,
[c] BASF Presentation, Chemical Nanotechnology for Sustainability, Dr. Stephan M. Altmann, Ludwigshafen.
[d] BASF website, innovation, nanotechnology: www.basf.com

the insulating capacity of traditional materials in a thinner panel.[a] Currently this product is used to ensure shipping containers maintain an appropriate temperature for extended periods of time.[b] This research is being publicised as moving into the nano-scale. This type of product may have far wider applications in the future than the relatively narrow current applications. In terms of environmental benefits this type of product has the potential to deliver significant improvements in insulative properties compared to current products, but release and wide scale use of these products is not likely to occur in the short term.

Aerogels are another area of research interest, occurring firmly within the nanotechnology scale. These products are very low density solids, typically composed of 90-99.8% air, structurally resembling a sponge at the nano-scale. Aerogels are excellent thermal insulators, their structure serving to prevent almost all conduction, convection and radiation. The use of aerogels as a replacement material for windows is an area of intense interest. Their use would offer dramatically improved thermal insulation properties over the highest performing glass currently available. However technical issues remain to be solved; aerogels are fragile, and not completely transparent. Development work is being performed to address these issues.

4.5.2 Potential Policy Implications

Advances in insulation could allow tougher new build Building Regulations without significant additional expense to the builder or house buyer. This would require careful redrafting of the Part L building code. The use of nano-insulation may require new work best practices to ensure the safety of the installer.

As the percentage of cavity wall insulated houses increases through retrofitting, other areas of high heat loss, such as windows, may become the focus. Nano-enabled glass may improve thermal insulation under such circumstances.

4.5.3 Route to Market

The development of novel materials and products exploiting nanotechnology could be encouraged through initiatives such as the from DTI Technology Programme funding and assistance with licensing IP schemes to encourage research developments to grow into products and move onto the market. The large insulation producers provide an ideal route to develop new products. Innovation through university structure

[a] Dow news release, 11.03.2002
[b] Dow Chemical Company website.

should easily find a route to market if it could provide enhanced insulative properties and/or could provide insulation for a situation where there are currently no solutions provided. The adoption of products developed to address the need for solid wall insulation could be encouraged through promotion and incentive policies similar to those currently used to encourage the adoption of cavity wall insulation. This segment of the housing stock, although likely to be reducing slightly year by year, will still represent a significant proportion of homes for a considerable time and so is a very stable market area to invest in.

4.5.4 Barriers to Market

Aerogels and VIPs may be suitable for applications where no appropriate insulation products currently exist. However they are unlikely to replace standard products in the future as the financial costs are substantial. These products may become more attractive if the thermal efficiency standards for new homes are increased out of range of performance of current insulation - a situation that currently appears unlikely.

Barriers are therefore the low demand for novel insulants and the relatively modest insulation standard requirements in the UK compared to the capability of conventional materials. A technical challenge remains in the aesthetic insulation of solid walls, but claims of the potential of nanotechnologies in this area are tenuous.

4.5.5 Potential environmental impact

If a paint-on insulation can be developed which has similar insulation properties to current insulation there is a potential saving to be made in the region of 5.2 Mte p.a. by insulating all non-cavity walled dwellings in the UK.[a] An insulation that provides similar properties to standard insulation without the associated issues of installation is more likely to be used, therefore the contribution of a new material is likely to be significant.

4.5.6 Recommendations

It is clear that there is a technology gap in the insulation of solid wall dwellings which may be addressed by the use of nanotechnology. There are questions over the current applications of a paint-on insulation for solid walled buildings and further research needs to be completed in this area. While new insulation products that deliver greater levels of insulation using smaller volumes of material will continue to be in demand, working

[a] Review of Sustainability of Existing Buildings, Department for Communities and Local Government, 2006.

at the nano-scale may not be necessary to achieve potentially innovative solutions. The recommendations from this investigation are:

- Maintain the high profile of standard insulation schemes, strongly encouraging the adoption of retrofit cavity wall insulation and loft insulation – this will have a more significant environmental benefit than nanotechnology over the short term.
- Initiate a funding call for innovative research into insulation for solid wall housing that doesn't require significant renovations. This research will probably fall under a DTI Technology Programme call.
- Encourage the adoption of more thermally efficient insulated windows than required by Building Regulations Part L through public procurement to government buildings.

4.5.7 Conclusions

Despite recent initiatives there is still a great deal that could be done to improve the quality of insulation in the nation's buildings. While this situation has recently been improved through Building Regulations, maintaining the momentum and further increasing the insulation quality of new buildings would be of benefit. The application of retrofit insulation, although widely publicised, has had limited take up. This may be acutely so in the non-residential building sector.

Research into identifying and creating novel insulation products is being conducted, both with respect to improving current products and to creating novel products which would provide solutions to unaddressed issues. Any new products will most likely have to compete with current mass insulation products on the market which are very effective and cheap to install; these therefore represent a significant barrier for new technologies to overcome. Although there is a great deal of discussion concerning the use of nanotechnology, much of the research that is underway does not incorporate nanotechnology aspects. There is much work remaining before solutions at the nano-level represent a way forward for insulation.

5 Recommendations

The barriers and recommendations highlighted in Section 4 focus on specific nanotechnology areas. This section details more general recommendations for the adoption and exploitation of, and barriers to, environmentally beneficial nanotechnologies.

5.1 Exemplar international policy models

It is important to compare the UK's policies and actions towards nanotechnologies with other governments' responses. Generally national nanotechnology infrastructure is judged on the following five criteria:

- large scale government funding (more than £40 million per annum)
- a national initiative with a pure nanotechnology focus
- world class dedicated nanotechnology facilities
- national networks/clusters
- holistic approach to research, development and commercialisation.

Research commissioned for this report has identified several models for national development of nanotechnology.[a] Based on the above criteria, the United States, Japan and Germany are leading the way. Most other countries, such as China, are playing catch up in terms of their knowledge and skills base. Other countries have failed to capitalise on their position, for example France, or have failed to develop a dedicated programme or incorporated nanotechnology under a wider area, for example the UK. However, within Europe, after Germany, the UK is widely considered to be one of the front runners for innovation in nanotechnology. Table 11 below describes national programmes for selected countries against the criteria outlined above. Appendix 4 contains further information surrounding national approaches to nanotechnology.

[a] Report commissioned for this report, Institute of Nanotechnology, 2007.

Table 11: Countries worldwide with high level nanotechnology activities and relevant world class criteria

Country	1. Large govt. funding	2. National initiative	3. World class nano facilities	National networks /clusters	Holistic approach
USA	✓	✓	✓	✓	✓
Japan	✓	✓	✓	✓	✓
Germany	✓	✓	✓	✓	✓
Taiwan	✓	✓			
South Korea	✓	✓			
UK	✓		✓	✓	
Ireland					✓
Australia		✓		✓	✓
Singapore	✓		✓		✓
Sweden				✓	✓
Denmark			✓	✓	✓
Finland	✓	✓		✓	✓
France	✓	✓	✓	✓	✓
The Netherlands	✓		✓	✓	✓
Switzerland				✓	✓
China	✓	✓	✓		✓

(Source: Technology Transfer Centre, 2007).
Key: Already implemented
Key: In process

It is important to highlight other national approaches in nanotechnology where the UK is perceived to be weak. There appears to be a deficiency in developing research through to commercial products. In Germany, a strategy entitled "Nanotechnology Conquers Markets" has been implemented which has the following industry focused programmes:

- Nanomobil (automotive)
- Nanolux (optical)
- Nanoforlife (life sciences)
- Nanofab (Electronics).

These schemes actively encourage industry to develop nanotechnology within these areas.

Japan's strategy for commercialising nanotechnology is based on a systematic plan broken into four broad areas:

- Basic research: the fundamental science of nanotechnology.
- Generic technologies: fabrication and measurement technologies.
- Challenge type projects: new technologies that will allow greater incorporation of nanotechnology.
- Flagship type projects: projects which focus on nanotechnology applications within the next 5-10 years.

This strategy should cover all aspects of commercialising nanotechnology. The USA has The National Nanotechnology Initiative, which, like Japan, breaks nanotechnology into several key areas.

The UK's deficiency in this area has been recognised and it is hoped that the Micro and Nanotechnology Knowledge Transfer Network will address some of these issues. The MNT KTN is due to be officially launched in summer 2007.

5.2 Lessons from other high technology industries

Although this report does not focus on the potential toxicological impacts of the nanotechnologies, the public perception of nanotechnology could be a significant barrier to its development. To this end, it is important to draw a comparison between this technology and other technologies where there are both potential environmental benefits and potential health implications; namely genetically modified (GM) food stuffs.

Across Europe, it has been estimated that if 50% of the maize, oilseed rape, sugar beet and cotton were grown as herbicide- or insect-resistant GM strains, the amount of herbicide used would decrease by 14,000 tonnes[a] with a modest decrease in CO_2 emissions. However Europe has chosen not to develop GM agriculture and the incorporation of these foodstuffs into its diet.

It is beyond the scope of this report to comment on the potential risks of GM food (and the validity of those risks), but parallels can be drawn between this technology and nanotechnology. Before 1996 the public and media were generally in favour of GM food stuffs,[b] which were seen as a potential method to reduce food shortages in the developing world. However, over the next few years, public opinion turned against GM technology to a point that 'GM free' is a selling point in supermarkets and restaurants. In the USA, there is less opposition to GM; one reason cited has been the general lack of information available to consumers. It appears that the potential risk of the technology, coupled with the public's distrust of the science, outweighed arguments for the technology that were presented.

In 2004, the Royal Society commissioned a study investigating the public's opinion of nanotechnology. The overwhelming majority, 71 %, had not heard of nanotechnology. Of those who had, opinion towards nanotechnology was largely positive. The speed with which opinion changed towards GM has resulted in a more cautious public engagement exercise[c] for nanotechnology to ensure that public opinion is gauged. However there are criticisms of this method, which has the public in a

[a] "Environmental benefits of genetically modified crops: Global and European perspectives on their ability to reduce pesticide use" R.H. Phipps and J. R. Park, Journal for animal feed science, 2002, 11, 1-18.

[b] GM: the rise and fall of GM, Channel 4 television, Equinox, 2001

[c] Nanotechnology: Views of the general public, Quantitative and Qualitative research carried out as part o f the nanotechnology study for the Royal Society and the Royal Academy of Engineers working group on nanotechnology. 2004.

passive role rather than contributing to the debate.[a] Moving forward, it is important that the public's concerns are addressed and that the fundamental research is in place to allow the public to make an informed choice.[b] Without this type of engagement there is a risk of nanotechnology becoming perceived as detrimental either to human health or to the environment at large. Ultimately, the largest barrier to nanotechnology could be the potential public concerns on safety.

It seems clear that an open, informed debate on the issues surrounding nanotechnology is the most effective way to ensure that there is public support for the development of this new technology.

[a] "The GMO-nanotech (dis)analogy" Ronald Sandler, Bulletin of Science, Technology & Society, Vol 26, 2006, 57-62.
[b] "The future of nanotechnology: we need to talk" Nanologue, 2006

5.3 General nanotechnology recommendations

Each product group outlined in Section 4 gives recommendations specific to that technology. Some generalised recommendations would be beneficial to policy makers when determining future policies for environmental nanotechnologies. However, the scope of nanotechnology prohibits insightful recommendations. Below are details of how, by subdividing nanotechnology, meaningful general recommendations can be made.

5.3.1 Nanotechnology sectors

Nanotechnology is not a single technology but a suite of different specialties which are working on objects in the nanometre scale. Therefore any statement must be specific to a particular area or technology. However it is possible to group certain technologies based on their properties or construction. Two identifiers have been chosen to group nanotechnologies:

- **Level of integration into wider systems**. This is a metric of the level of control or connection a nanotechnology has to an outside operator. For example, a nanotechnology with a low level of integration into a wider system would be the free nanoparticles used as catalysts in fuel additives, whereas a nanoparticle connected via organic molecules into a large array for use in a photovoltaic cell (such as a Grazel cell) would have a high degree of integration into a wider system. This is a measure of the degree of control that is required over the nanotechnology and is not itself concerned with the nanotechnology.

- **Level of complexity of nanomaterials**. This metric focuses purely on the technology required to develop the nanotechnology and the complexity of the nanotechnological structures. For example ceramic nanoparticles are relatively simple spheres of atoms of varying sizes, whereas 'molecular machines', which build intricate and varied nanostructures from atoms and molecules, would be considered a 'complex' nanomaterial.

These metrics are to a certain degree subjective and time specific (any placement against either will change over time as technological advancements make integration or synthesis of the nanostructure more feasible). They also form a continuum from the simplest isolated structures to the most complex integrated technologies. For simplicity, if the nanotechnology is classified as either a simple or complex structure and either as isolated or integrated then all nanotechnologies can be described in one of four ways (see Figure 2).

Figure 2: The subdivision of nanotechnology by complexity of the nanostructure and the level of integration into a larger system

Measure of complexity of developing a product →	**Integrated**	Simple nanotechnologies with a high degree of integration into a larger system. For example nanoparticles in photovoltaic cells.	True integration of complex nanotechnologies with real world systems. For example the ideal NEMS systems or site selective nanosensors integrated into larger arrays.
	Isolated	Nanoparticles or thin films in simplistic uses. For example fuel additives and spray-on window catalysts.	Complex molecular machines which operate autonomously from a larger system. For example chemical sensors / indicators for detection of specific toxins.
		Simple	**Assemblies**
		→ Measure of complexity of nanotechnology or science behind nanotechnology	

The development of a grid allows a crude estimation of the technical challenge that a nanotechnology faces before reaching the commercialisation stage. In general, simple nanotechnologies are easier to synthesise than complex assemblies. In a similar situation, isolated nanotechnologies are easier to develop than integrated systems. A combination of these two metrics will give some indication of the degree of 'difficulty' of developing a nanotechnology. For example:

- Isolated assemblies are probably more technically challenging than isolated simple systems.
- Greater integration of simple systems is likely to require greater development than isolated nanotechnology.
- Integrated simple systems face different challenges to isolated assemblies.
- Integrated assemblies are probably the most technically challenging nanotechnologies to develop.

However this system does not comment on any other aspect of the product; it only gives an indication of the relative challenges that the nanotechnological aspect of a product will bring to the overall development. As an illustration, nanoparticles of a metal hydride are a potential material for hydrogen storage. The nanotechnological aspect of developing these materials appears to be relatively straightforward; however the materials science to develop the materials is a significant challenge. Therefore this product is several years away from commercial application due to the development of the appropriate materials, not the nanotechnology.

Without subdividing nanotechnology using this method it is difficult to identify generalised barriers that are preventing the technological development of nanotechnologies.

5.3.2 Barriers and failures

The subdivision of nanotechnology into four groups enables the potential barriers to be highlighted which are specific to one of the subdivisions (see Figure 3).

Figure 3: Barriers preventing the development of nanotechnology

Measure of difficulty of developing a product →

	Simple	Assemblies
Integrated	Difficulties in translating technology into workable devices. Fundamental science is thriving but need enablers to drive the technology to prototype	Fundamental research is in the early stages: integration is a major issue. Difficulty in finding true benefits due to early stage research
Isolated	University/SME/start-up /VC/industry infrastructure in place to exploit technology. Public acceptability and risk are an issue.	Translating 'bench top' nanotechnology into production is difficult. Large scale manufacturing techniques are lacking.

→ Measure of complexity of nanotechnology or science behind nanotechnology

It is relatively easy to develop simple isolated nanotechnologies for commercialisation. Essentially, once a nanotechnology has been developed on a research scale, there are few barriers within this subdivision that are unique to nanotechnology. Issues such as scale-up, large scale testing and commercialisation are common in many areas of science and technology. The support and commercialisation infrastructure for these nanotechnologies are well defined, such as university commercialisation units, start-up/spinout companies, DTI Technology Programme funds, venture capital and industry. The issues and potential solutions to these problems have been highlighted in several reports.[a] The main barrier is likely to be public perception and risk.

The technological barriers preventing the development of integrated simple nanotechnologies are focused around the integration of the nanotechnology into the wider system. The development of the nanotechnology itself does not pose the most significant problem. From this it can be reasoned that there is a knowledge transfer and capabilities gap in the UK preventing the development of integrated nanotechnologies. Fundamental university research into nanotechnologies which possess the potential to be incorporated into larger systems is failing to deliver products because the skills of the original researcher are likely to be unsuited to the integration and development of a prototype. This development type of research is also less suited to the university remit, which is to perform pure and applied research, not develop products.

In the commercial sector, the potential to commercialise these nanotechnologies or develop meaningful IP is also limited due to the research being at a very early stage of development and therefore requiring significant investment. Part-funded government research grants (such as the Technology Programme) which fund commercial development projects are unlikely to encourage companies to invest in this type of research due to its high risk. The lack of any high-tech multinationals with large scale in-house R&D budgets also compounds the problem. SMEs and start-up companies do not have the resources to invest in the development of these integrated nanotechnologies, where several years of research are needed before a commercial product is produced. Due to the extended timescales and obvious high risks involved in developing these products, the venture capital sector is pessimistic about investing in these types of ventures.

The technical barriers for free assemblies are significantly different to simple integrated nanoparticles. The barriers for these technologies are the development of the nanotechnology itself. The application of the nanotechnology should be relatively simple if the technology functions autonomously. The main barrier will be in developing a suite of skills which allow the production of these nanotechnologies both during development and in final production. This is a classic chemistry problem

[a] Lambert review of business-university collaboration, 2003

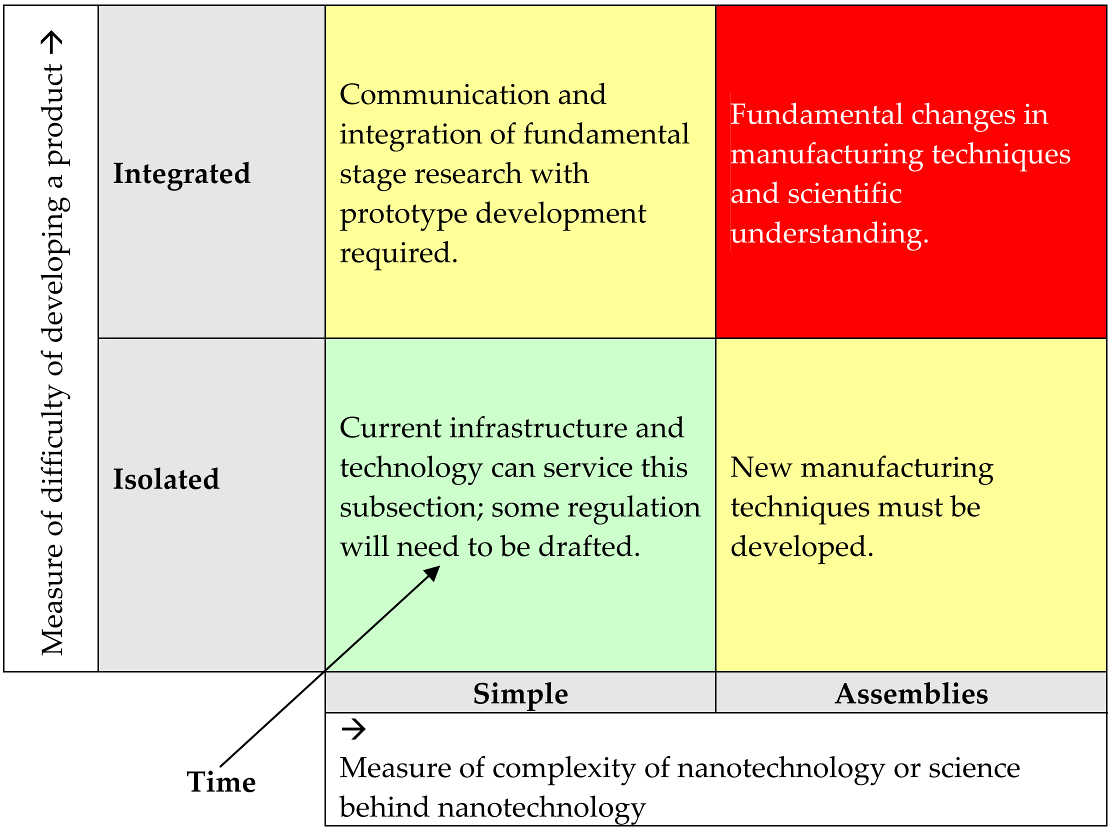
of 'scale-up'; products which can be produced on an experimental scale but cannot necessarily be translated into commercial production.

Integrated assembly nanotechnologies have problems of both the wider integration of the nanotechnologies and the synthesis of the nanotechnology itself. The complexity of the problems facing integrated assemblies is likely to limit their research. Conventional scientific logic dictates that research into simple integrated and isolated assemblies of nanotechnologies should be performed in order to build the knowledge base from which the area of integrated assemblies can be addressed. However, the techniques developed to address the problems of simple integrated and isolated assemblies may not be directly transferable into integrated assemblies, and therefore an entirely new set of techniques may need to be developed.

Although not unique to nanotechnology or the simple isolated nanotechnology subsection, issues of product regulation are probably most acute in this subsection. These nanotechnologies are closest to commercialisation and are less likely to be contained within a system. Therefore it is likely that the public's first contact with nanotechnology will be with this subsection. The, as yet unknown, health risks (and the spectre of GM) may result in over-regulation or public backlash. This uncertainty results in unfavourable conditions for businesses to flourish.

Nanotechnologies are becoming more prevalent in products ranging from cosmetics to golf clubs. Generally the materials used are essentially isolated free nanoparticles. Some of the nanotechnologies used verge on integrated simple and isolated assemblies. These current technologies are based on traditional manufacturing and development technologies. As progress is made in these areas, new, 'nano-specific' synthesis and manufacture technologies are likely to emerge which will increase the availability of more complex nanotechnologies. Figure 4 shows key technological and infrastructural changes which are required to enable nanotechnologies to enter mainstream production.

Figure 4: Technological and infrastructural changes required to enable nanotechnologies to enter mainstream production



The ultimate outcome of using nanotechnology is a fundamental change in the manufacturing techniques of the industries that it impacts on. A crude timeline can be plotted starting in the bottom left and moving toward the top right. There is only a small change in manufacturing techniques required to bring simple isolated nanotechnologies through to commercialisation. New techniques in integration are required to bring simple integrated nanotechnologies through to commercialisation, whereas novel manufacturing techniques are required to develop advanced isolated assemblies. A fundamental shift in production techniques will be required (incorporating both techniques for integration and assembly) for the development of integrated assembly nanotechnologies.

The speculated uses can sometimes be considered a 'magic bullet' technology. This report has shown that nanotechnology, even in the short term, will play a role in reducing our impact on the environment. The reasons for this are that the near market EBNTs are focused in the bottom left of Figure 4, which involve developing nanotechnologies based on 'traditional' techniques. Therefore, the benefits of using nanotechnology within this simple isolated subsection are generally going to be limited to a simple increase in efficiency or a reduction in cost over current technologies. The large environmental benefits which nanotechnology can deliver are likely to be realised in the medium term by development of nanotechnologies within the simple integrated and the isolated assemblies in the medium term, and ultimately in the integrated assemblies subsection.

5.3.3 Exposure and toxicology

The subdivision of nanotechnology allows more detailed understanding of the toxicological and exposure risks. Figure 5 shows the risks associated with various subdivisions of nanotechnology.

Figure 5: The toxicological and exposure risks and potential mitigations for nanotechnology

Measure of difficulty of developing a product →

	Simple	Assemblies
Integrated	Entrapped or encased nanoparticles, likely to be 'remote' from the general public	Likely to fall under REACH but also remote.
Isolated	Simple, common compounds which are easily deployed. Potential unknown risk to human health.	Probably chemical based systems (potentially very toxic). REACH regulations likely to protect the public.

→ Measure of complexity of nanotechnology or science behind nanotechnology

Isolated simple nanotechnologies are currently being introduced onto the market. These compounds are generally 'smaller' versions of traditional products with enhanced functionality. Such products potentially pose the greatest exposure risk to the public but are also products where the bulk properties have been extensively investigated. Indeed, the current debate on the safety of nanotechnology largely revolves around these compounds where, in essence, they are generally simple inorganic compounds which have been fully characterised, but on the nanoscale pose new risks unforeseen on bulk samples. Although the benefits of these nanomaterials are modest compared to potential future nanotechnologies, comprehensive investigation of the risks and benefits of nanotechnologies at this stage will assist in the acceptance (or otherwise) of more sophisticated nanotechnological approaches at a later stage.

The toxicology of integrated simple nanotechnologies is likely to be similar to isolated simple nanotechnologies. However, as the level of integration of the nanotechnology increases, it is likely that the exposure to the nanotechnologies, at least towards the end user, will decrease. Therefore, although the toxicological effect of the materials might be similar, integrated simple nanotechnologies are inherently safer than isolated simple nanotechnologies. However there is still a significant risk of exposure to these compounds for nanotechnology manufacturers. There will also be end of life issues with these technologies where safe disassembly and recycling/disposal must be accomplished.

Isolated assemblies are likely to be completely novel materials. Therefore, as with any new material, they will fall under existing chemical regulations on safety and use (for example REACH, the Cosmetic Directive, FDA approval). In the near term, the public's exposure to these materials is likely to be limited mainly because the majority of technologies employing these nanomaterials are still in the early research stage. As these materials become more widely available there will be a need to examine end of life issues of these compounds.

Integrated assemblies are likely to fall under current chemical regulations and they are also likely to give rise to limited exposure due to their integration into a larger system.

5.3.4 Sectoral Policy recommendations

Isolated simple

- Health and safety testing is required to ensure that the products pose no human health risks. The materials used to make such nanomaterials are unlikely to be completely new and safety data may be available. On the nanoscale, however, unusual toxicological effects may arise. Also the public is likely to come into direct contact with these materials, increasing exposure.
- Where appropriate, procurement policies should be adopted to encourage the commercialisation of EBNTs. Intervention of government to help demonstrate environmental impact claims and to purchase the technologies itself, hence ultimately lower prices through

economies of scale is desirable. Innovative products could give advantages through voluntary codes or efficiency regulation.[a]

- Research calls that deliver EBNT should be supported through Science Councils and programmes such as the DTI Technology Programme.
- Industry-led demonstration projects showcasing EBNTs should be funded
- Stakeholders should be engaged to adopt working best practices for manufacture and end of life of EBNTs.

Simple integrated

- Build and develop technology specific (for example photovoltaics) centres of excellence that incorporate researchers and engineers from a wide variety of disciplines.
- Strong consortia led by large internationally recognised companies will increase the probability of UK based research being commercialised.
- Fundamental research considering the integration of nanotechnology into larger systems is required.

Isolated assemblies

- A research focus on bulk manufacturing of nanomaterials is required. This includes the production of films and nanoparticles and assemblies.
- Encourage interdisciplinary research to develop solutions to large scale manufacture of nanomaterials.
- It is important that the reduction in the number of science and engineering graduates in the UK is reversed. Although universal to all areas of nanotechnology, within this sector fundamental science is required to drive commercialisation.

Integrated assemblies

- Continue to fund 'blue sky' research into advance materials and integration technologies.
- Develop links with the multinational ICT manufacturers.

[a] Precedents such as boiler efficiency or part L building regulations have significantly increase energy efficiency of new houses.

5.4 Recommendations with relevance to the Stern Review

This study examines nanotechnologies which have the potential to reduce GHGs and thus reduce the severity of climate change. Part IV of the Stern Review details mitigations (and failures) to enable the delivery of low carbon technological advances. It is important to draw comparisons between barriers and recommendations surrounding the development of environmentally beneficial nanotechnologies covered by the report with those facing other environmentally beneficial technologies. Table 12 details a selection of recommendations from the Stern Review and their relevance to this report.

Table 12: Comparison between the Stern Review and the comments and recommendations made in this report

Stern Comments[a]	**Relevance to environmentally beneficial nanotechnologies**
The global budget for research and development in energy should be doubled.	It is clear that further fundamental and applied research into nanotechnologies is required to deliver the benefits outlined in the report. For example there is a need for fundamental research into the development of solid wall insulation.
The public should be engaged and informed about environmentally beneficial technologies.	Toxicological studies into the effects of (for example) fuel additives is imperative if the public's fears are to be allayed.
Deployment incentives should increase five fold to allow new low carbon technologies to be competitive.	The subsidy for carbon intensive electricity generation approximately $150-250 billion world wide. Reallocation of these subsidies would enable systems such as nano-enabled photovoltaics in a distributed grid to be more widely implemented.
Global pricing of carbon and energy is uncertain, which results in under-investment in low carbon technology.	Within Europe, investors in new battery technology are reputedly unwilling to commit to long range projects. The uncertainty in regulation and post-Kyoto targets are probably compounding their lack of enthusiasm to invest.
In the absence of a niche market, the research costs are borne by innovators, who are competing with established high carbon alternatives.	Most of the technologies described within the report are competing with low cost, high carbon alternatives. Intervention will probably be required to enable the deployment of these technologies.
The electricity infrastructure favours centralised plant.	This is a barrier for all microgeneration technologies.

[a] These comments are drawn from The Stern Review: The economics of climate change, 2006, Part IV pages 347-376

Stern Comments[a]	**Relevance to environmentally beneficial nanotechnologies**
New vehicle networks (namely hydrogen and electric refuelling points) are unlikely to be developed without government intervention.	The move to zero carbon transport is likely to involve the use of nanotechnology. However, at present there is very little market pull to invest in the infrastructure (refuelling stations) to make zero emission transportation attractive to the public.
There is a need to develop new methods of hydrogen storage and generation.	This is key to the development of hydrogen as an alternative energy store. Nanotechnology is seen as the front runner in developing these technologies.
Hydrogen bus demonstration projects are a promising method for utilising hydrogen.	Until the issues surrounding storage are resolved the most practical use of hydrogen power is in buses where space limitations are reduced. The efficiency of the fuel cells can be improved in these studies.
A portfolio of technologies should be developed; although there is inherently a higher cost, the overall risks of developing a successful solution are minimised.	This nanotechnology report outlines several technologies which are competing within the same area. The ranking methodology has given some indication of the feasibility of the technologies, however, it would be dangerous to focus on a small selection of technologies.
Incremental changes in efficiency do not usually require support for deployment (other than institutional barriers).	Simple free nanoparticles (Section 5.3.1) are examples of near term technologies which may offer incremental improvements in efficiency. Barriers facing their entry are common to other product developments and launches, however, these substances may pose health risks.
More engineers and scientists will be required as the development of low carbon technologies increase.	This is crucial in nanotechnology, which uses expertise from chemistry, physics and engineering. These subjects have seen declining percentage of graduates in the UK in recent years.
The funding of demonstration projects should be used to develop new low carbon technologies	Hydrogen bus demonstration projects should be maintained and expanded. Fuel additives demonstration project should be carried out.
Further research is required into energy storage technologies to allow the use of low carbon electricity in transport.	The development of hydrogen fuel cells and new battery technologies will contribute to this area

5.5 Summary of technology specific recommendations

This section summarises recommendations for the nanotechnologies described in Section 4. Table 13 identifies which policy intervention strategy each recommendation falls under. This can be compared to the various strategies implemented either on a UK or EU level defined in Appendix 3.

Table 13: Summary of the recommendations for the 5 nanotechnologies reviewed in Section 4.

	Regulation	Research Funding	Demonstration and Diffusion	Procurement	Economic Instruments	Standards / Mkt Transformation	Awareness and Communication
Hydrogen Economy		Develop high level links with the automotive sector and research into hydrogen storage techniques	Expand the hydrogen bus demonstration projects				
Electricity Storage	Engage on issues of end of life vehicles	Enable long term research projects		Encourage large fleet procurement of battery powered vehicles	Fiscal incentives for vehicle ownership (such as congestion charges)		Engage with stakeholders for electric vehicles infrastructure
Photovoltaics		Develop centre of excellence for PV Develop funding for pre-commercialisation		Use energy efficient stand alone products	Revise taxation regime to level micro generation playing field	Ensure that new-builds obtain certain percentage of power from renewables	
Insulation		Research novel insulants call through the DTI-TP		Advanced window procurement for governmental offices		Increase insulation requirement for Part L – windows on new builds	
Engine Efficiency	Research into toxicity of airborne nanomaterials	Use DTI/EPSRC funding for catalytic converters	Trial of fuel additives				

6 Summary

In the near term, the use of nanotechnology as a fuel additive could reduce GHG emissions by approximately 2.1 million tonnes with little infrastructural change. However, the toxicology of the material must be investigated to allay public concerns. There is a gap in the insulation market of non-cavity walled homes, which could be filled using nanotechnology but this will rely on the development of new super-insulating materials. There is potential to reduce the 5 Mte of GHG lost annually in the UK through poor insulation.

Nanotechnology appears to be the solution to reducing costs and increasing efficiencies of photovoltaics. The overall reduction in GHG emissions in the UK is likely to be relatively small, purely due to the UK's geographical latitude. However, the global effect of nanotechnology on photovoltaics is likely to be large.

Both hydrogen fuel cells and batteries offer solutions to remove our reliance on fossil fuels for road transport. These technologies could decouple transport from GHG emissions if the UK's electricity generation uses low carbon sources. Even using the UK's current energy generation mix, there are significant health benefits and efficiency savings in generating energy (either hydrogen or electricity) at a centralised location outside major population centres. Hydrogen fuel cells are likely to use nanotechnology to improve efficiencies of the fuel cell, increase storage capacity and help generate hydrogen. Nanotechnology in batteries will enable fast charge/discharge batteries and increase overall capacity. Although these two technologies are competing, the current capabilities of hydrogen and batteries are complementary. Hydrogen use, due to limitations in space, favours large vehicles such as buses and commercial vehicles, whereas use of batteries favours smaller vehicles, such as cars, due to limits in power and safety.

More generally, by measuring nanotechnology on its complexity and level of integration into a larger system, meaningful barriers can be identified and recommendations can be reached. Issues surrounding toxicology and exposure can also be considered.

Nanotechnology is a relatively 'young' science, therefore there is a need for significant research and development expenditure before the science yields large breakthroughs. In certain examples, however, nanotechnology is mature enough to be readily incorporated into products. Under these circumstances, the social and political barriers dominate. The incorporation of nanotechnology into larger systems may also be a major barrier in the development of new products.

Over the coming decades, nanotechnology is predicted to become ubiquitous and to revolutionise the functionality of products. However this view needs to be tempered by findings from this report. The near term effects of nanotechnology are significant, yet incremental. The long term predictions for some of the technologies are larger, but they probably underestimate technological advances in non-nanotechnological innovations. Overall though, the potential advances brought by nanotechnology justify continued interest in the area.