NanoRoadMap is a project co-funded by the 6th Framework Programme of the EC

Draft RoadMap on Solar Cells

The Institute of Nanotechnology

October 2005

Partners

1. Introduction

1.1 Background

The NanoRoadMap (NRM) project, co-funded by the European Commission (EC), is aimed at road-mapping nanotechnology related applications in three different areas:

- Materials
- Health & Medical Systems
- Energy

Within the project, an international consortium consisting of eight partners covering eight European countries and Israel, has joined forces to cover the time-frame for technological development in this field up to 2014. The results of the NRM project are to be used by any European entity interested in planning an R&D strategy taking into account nanotechnology. An important potential user is of course the EC itself in the preparation of the 7th Framework Programme (FP7) for research and technology development. For additional information on the NRM project, please refer to www.nanoroadmap.it

1.2 Goals

The primary objective of NRM is to provide coherent scenarios and technology roadmaps that could help the European players to optimize the positive impact of nanotechnology on society, giving the necessary knowledge on its future development and when technologies and applications will come into full fruition.

The key users of the reports are mainly European SMEs, research organizations, public bodies in general and the EC in particular. Even though a special focus is put on SMEs, these roadmaps are also meant to be useful for larger corporations.

This report is one of the three final deliverables of the NRM project and it is aimed at providing a thorough overview of specific topics selected for road mapping within the field.

1.3 Methodology

1.3.1 Collection and synthesis of relevant existing information

In October 2004 three sectoral reports were published, each covering one of the above mentioned areas. They were based on the collection and synthesis of existing public sources in 31 countries and were published as key input for the celebration of the First NRM International Conference held in Rome the 4th – 5th of November 2004. The full report can be downloaded for free on the project web site.

The report within the energy sector focused on reviewing the different aspects of nanotechnology in 10 topics, giving its definition, describing its most remarkable properties, current and future markets and applications, and leading countries and highlighted R&D activities in the field. A general review of non technological aspects (social, legal, ethical and health and safety aspects, but also economical aspects and infrastructures requirements) was also performed.

The 10 topics identified, even not being completely homogenous in terms of scope or classification, were intended to adequately cover the field of energy. The following list was agreed upon the different partners of the NRM project (similar classifications can be found in the existing bibliography):

- Solar cells
- Fuel cells
- Thermoelectricity
- Rechargeable batteries
- Hydrogen storage
- Supercapacitors
- Insulation
- Glazing Technology for Insulation
- More efficient lighting
- Combustion

1.3.2 Selection of Topics

Another major goal of that report was to set the basis for discussion and selection for road mapping of 4 out of the 10 topics identified above. A preliminary selection of topics was presented during the First International Conference in November, 2004.

After a thorough discussion, which involved international experts in the field of nanotechnology, four topics were selected (and validated in dialogue with the European Commission). The subjects were partly combined with each other, leading to the four chosen topics:

- Solar cells
- Thermoelectricity
- Rechargeable Batteries and Supercapacitors
- Heat Insulation and Conduction

1.3.3 Roadmaps elaboration

One draft roadmap will be prepared for each of the four aforementioned topics. Their preparation and execution will be based upon a Delphi-like approach. The methodology consists of 2 cycles, which is the same for the four topics. The Delphi exercise consists in:

- Selecting top-international experts on the field
- Preparing a dedicated questionnaire for each of the topic to be road mapped
- Circulating the questionnaires and gathering experts' responses (1st cycle)
- Preparing a first summary of the given answers
- Circulating the summary and partly interpreted data, asking for feedback (2nd cycle)
- Elaborating the roadmap

Through one international and eight national conferences these reports will be proposed to the interested partners and comments collected so as to build up final definitive roadmap.

2. Road Map on Solar Cells

2.1 Definition of solar cells

Solar cells (also known as photovoltaics) convert the energy of the sun to electricity. The energy reaching the whole of the earth's surface is in itself sufficient to satisfy global electricity demand. A photovoltaic solar cell consists of a diode made of semiconducting materials sandwiched between two electrical contact layers. Sunlight passes through the top contact layer, is absorbed in the semiconductor and generates electrons and holes, which diffuse to the different contacts. The electrons and holes are separated by the diode and these charges drive a current in the circuit. DC electricity is generated when the solar cell is connected to electrical equipment (or load) such as lighting. Solar cells are integrated in larger modules and arrays, to generate enough electricity.

The spectrum of light which can be successfully utilised by the solar cell depends on the type and configuration of material(s) used. Silicon is the most common element used to manufacture solar cells however other inorganic and organic materials are being developed. Although efficiencies have increased, current mainstream applications fall far short of the theoretically achievable efficiencies, while remaining more expensive relative to other forms of energy production. Cheaper alternatives to silicon do exist however these have much lower efficiencies and often are more sensitive to environmental conditions.

Different types of solar cells and new materials being developed for solar cell technology are described below:

Crystalline solar cells

Crystalline technology produces the highest efficiencies (typically 20%), and currently silicon mono and polycrystalline solar cells dominate the market (80% share in 2000, which is expected to decrease to 70% by 2010). Cost is an issue with monocrystalline silicon cells which require pure semiconductor material of the quality used for computer chips (amounting to half the costs of the finished module). Polycrystalline is cheaper to produce however the irregularities in the matrix decrease the solar cell's efficiency.

Amorphous/thin films

This is a more cost-effective solution and uses a cheap support onto which the active component is applied as a thin coating. As a result much less material is required (as low as 1% compared with wafers) and costs are decreased. Most such cells utilize amorphous silicon, which as its name suggests does not have a crystalline structure and has consequently a much lower efficiency (8%), however it is much cheaper to manufacture. Such coatings can be applied to many different substrates including flexible ones and have applications where power consumption is low or large areas can be covered with the panels (e.g. integrated building panels). The other most common materials used are copper indium diselenide (CIS or, with gallium added, CIGS) and cadmium telluride (CdTe). Collectively thin film photovoltaics had a market share of approximately 6% in 2003.[1]

Organic dye sensitised

Also known as Grätzel cells (after their inventor Michael Grätzel) these consist of thin layers of titanium dioxide nanoparticles onto which organic dye molecules are adsorbed, and an aqueous or gel-like electrolyte. The process of energy conversion is similar to that used by plants during photosynthesis (electron transfer via dye molecules). The materials for such cells are cheap, however efficiencies are low (10% in experimental models).

Polymer cells

Semiconductor polymers are mainly organic molecules (such as polyphenylene vinylene) which have extended delocalised bonds that create a band structure similar to silicon.

Ultrathin layers of these molecules are used in cells which are cheap to manufacture, but suffer from low efficiencies and sensitivities to air and moisture.

Quantum dots

These are nanoscale crystals of semiconductor material which have different absorption and emission spectra that are dictated by particle size. Due to their small size they are potentially more energy efficient, generating up to three electrons per photon, compared to one with existing silicon technologies. They can be incorporated in different matrices and applied as thin films, potentially allowing a larger proportion of the spectrum to be absorbed (by using different sized particles in stacked layers).

Quantum wells

These are formed in ultrathin layers of low bandgap semiconductor material which are sandwiched between other materials of larger bandgap. They also allow potentially more energy to be captured from available light than materials in existing applications.

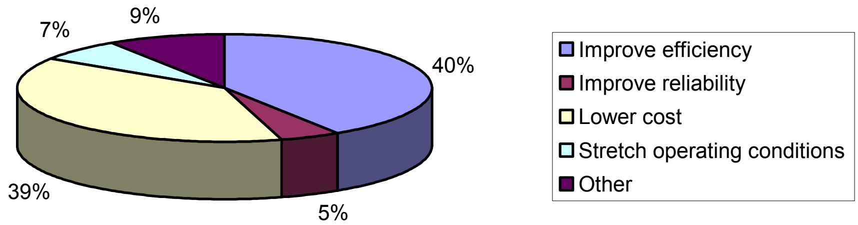
Carbon nanotubes and fullerenes

When incorporated in matrices of other semiconductor material, these facilitate charge transfer thus increasing efficiency. In addition they can be used as scaffolds for the deposition of other semiconductors, giving a much larger surface area per unit volume and boosting energy conversion.

2.2 Scientific and Technological Aspects

One of the major obstacles in the take-up of solar cell technologies is the cost of manufacture relative to efficiency of energy conversion, which is currently much higher than existing alternatives (such as fossil fuels). Although nanotechnology is not used in most solar cells at present, the experts that participated in the Delphi questionnaire are of the opinion that it will address this question, as the most revolutionary properties of nanoparticles in solar cells compared to existing/alternative technologies are seen to be their ability to improve the efficiency and to lower the cost of solar cells (see below).

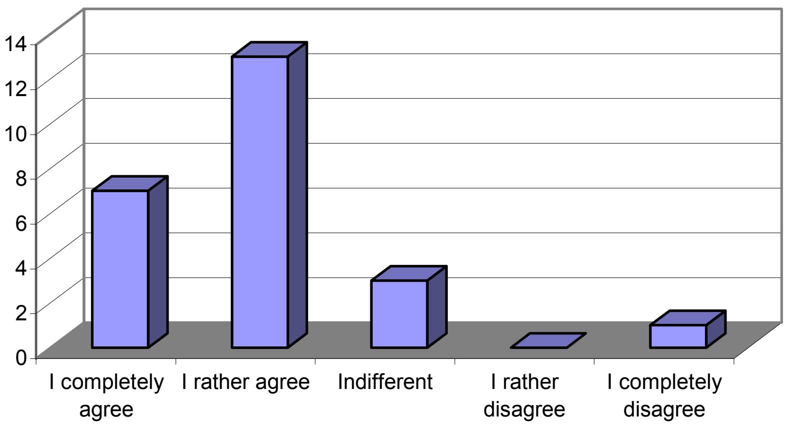
Most revolutionary properties in nanomaterials compared with existing technologies



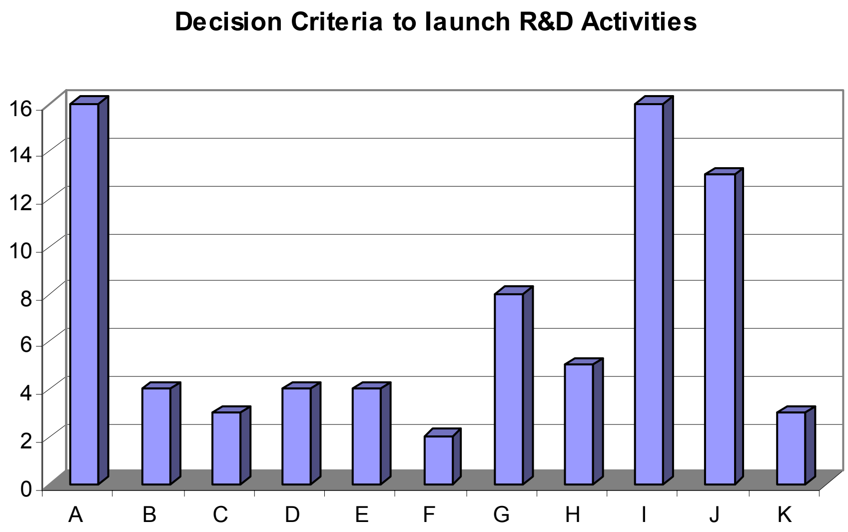
According to the experts nanoparticles will offer totally new development options and improvements which cannot be achieved with existing technologies, (see graph below), with solutions to the efficiency and cost issues through:

- development of thin films
- use of nanoparticles (and therefore increasing surface area)
- identification and development of new materials with new properties

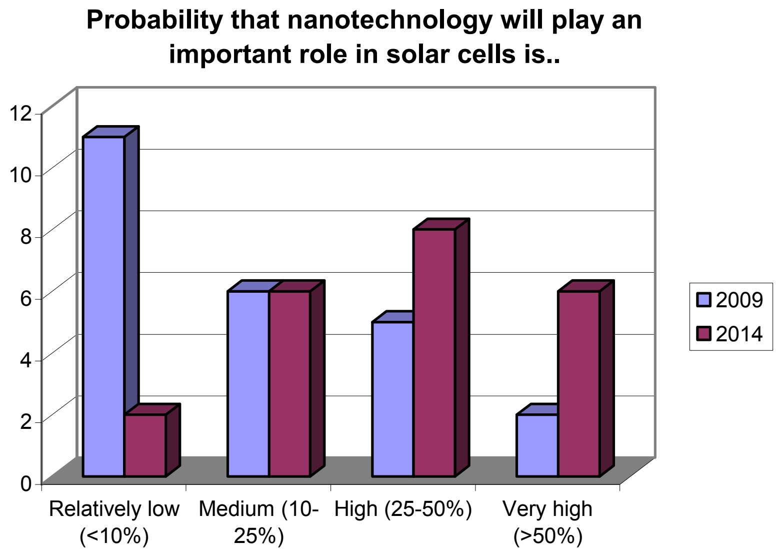
Revolutionary properties of nanoparticles offer totally new development options which cannot be achieved with other technologies



In fact one of the main driving factors in launching new R&D activities is the low-cost of future products (identified by two-thirds of respondents). The fact that scientific reputation is seen as equally important and that short time to market, product maturity and market entry are seen as relatively less important can be partially explained by the high number of academic scientists responding to this questionnaire. However most experts also believe that the impact of nanotechnology in solar cells will be relatively low even by 2009, indicating that it is in basic R&D where most activities will be focused.

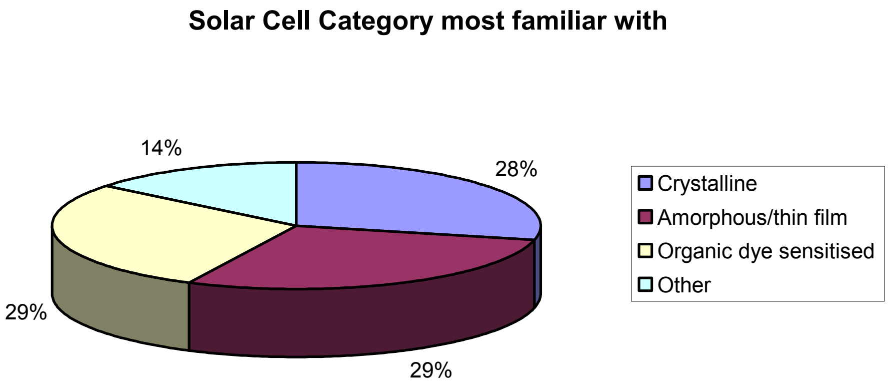


A. Low costs of the estimated product
B. Low costs of research process
C. Short time to market
D. Rapid readiness for start of production/product maturity
E. Specific market entry
F. Broad market entry
G. Possibility of governmental subsidy
H. Possible patent announcements
I. Scientific reputation
J. Possible publications in scientific journals of high reputation
K. Other (included: high impact of new product to solve mankind's energy problem; high efficiency and lifetime of estimated products; and relevance for application)

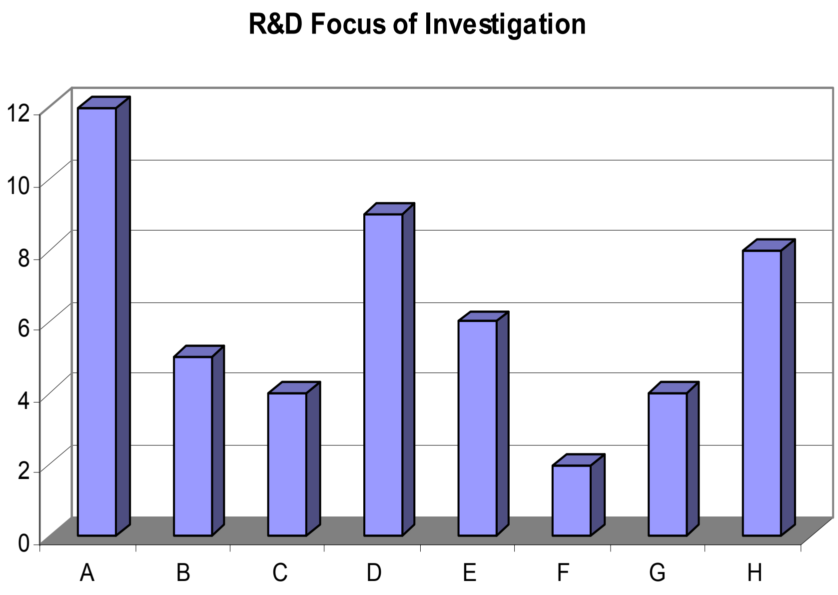


2.2.1 Basic Science

The experts contacted for the Delphi questionnaire have experience in a wide area of R&D topics (see pie chart below) including crystalline solar cells (28%); amorphous/thin film cells (29%); organic dye sensitized (29%); and other at (14%). The other category included: organic and composite cells; organic polymeric cells; 3D nanostructured solid state cells; and conjugated polymer based cells.



Most experts focus their R&D activities in a few areas with the most prominent being thin films (half of the respondents) followed by polymer-based and hybrid cells (see graph and key below). Some specific activities include improving efficiency of organic polymeric solar cells; bulk heterojunction by electropolymerisation; using nanostructured materials in 3D configuration; light trapping nanostructured polymers; ion conducting polymers, passivation and barrier layers for organic solar cells; and improving the efficiency of conjugated polymer cells.

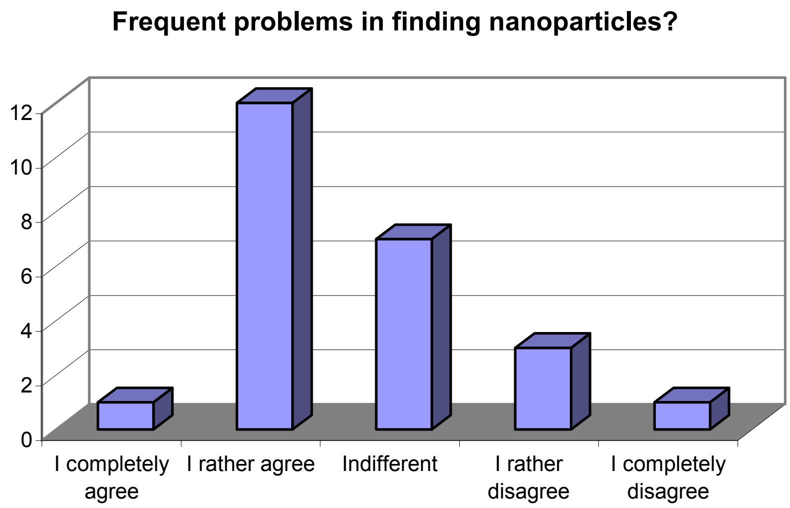


A. Improving efficiency of silicon solar cells eg. by applying thin films
B. Improving efficiency of dye-sensitised silicon solar cells
C. Finding a new group of dye molecules for the dye-sensitised solar cell
D. Implementing light absorbing nanomaterials in electrically conductive polymers
E. Embedding quantum wells (QWs) or quantum dots (QDs) in different inorganic or organic solar cells
F. Using inorganic or colloid quantum dots (InP, PbS, etc) as dye molecules
G. Using nanostructured materials such as Silicon or Germanium nanocrystals luminescence converters
H. Other

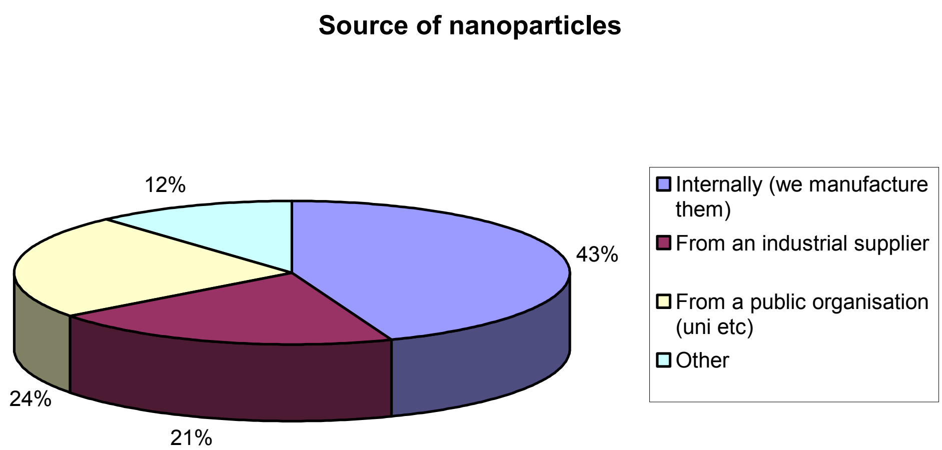
2.2.2 Nanotechnologies in Solar Cells – Value Chain

Production

Access to the right materials is a major issue with 54% of experts stating that they have frequent problems in finding nanoparticles to satisfy their R&D and/or manufacturing needs in solar cells. In contrast only 17% have few or no problems sourcing materials. The remaining 29% are indifferent about this matter.

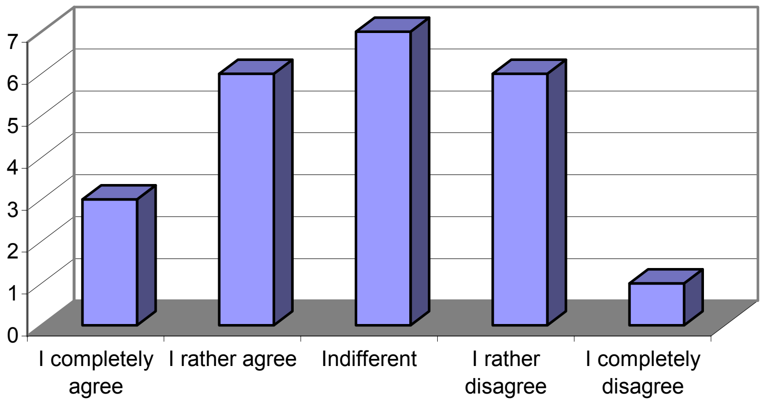


One of the reasons for this may be that the largest source of nanoparticles used in the respondents R&D activities are internally manufactured (see chart below) or from colleagues or public organisations. This can create bottlenecks in the development and testing of integrated devices which incorporate several different materials. There is also the issue of reproducibility between batches of internally manufactured materials, especially given the lack of nanoscale standards. Only 21% of materials were sourced from an industrial supplier, however a number of the experts used nanoparticles from multiple sources.



There was no decisive answer from the responses in answer to the statement "I know the bigger part of manufacturers/suppliers of nanoparticles being suitable for my specific goal". There is little correlation between difficulties in sourcing nanoparticles and knowing who the suppliers are, however although those who use nanoparticles from multiple sources know who most of the suppliers are, they are also most likely to have difficulties in sourcing material.

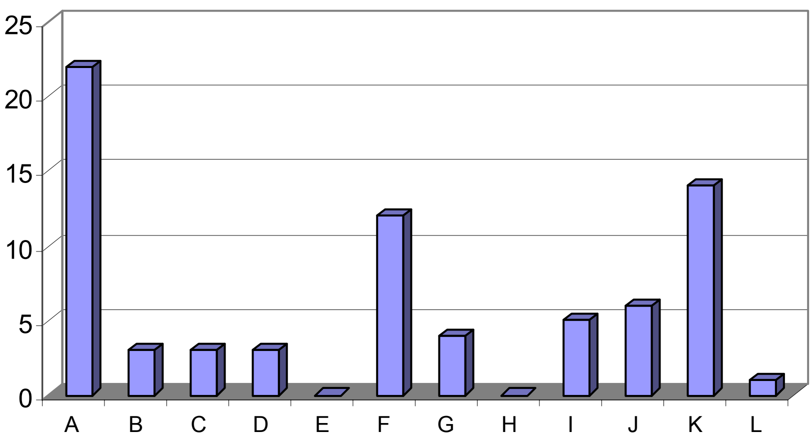
Know who most of the manufacurers/suppliers are of nanoparticles for specific use..



Functionalisation

Thin films, layers and surfaces are the most extensively used technology for R&D applications, followed by nanocrystalline materials and nanoparticles. Around one third of experts believe that it is still too early to predict what technologies will be most influential in the application to solar cell manufacture, however those who did express an opinion predicted that these three technologies would be leaders.

Most suitable type of nanotechnology for your specific goal in solar cells



A. Thin films, layers and surfaces
B. Carbon nanotubes
C. Inorganic nanotubes
D. Nanowires
E. Biopolymers
F. Nanoparticles
G. Fullerenes
H. Dendrimers
I. Quantum wells
J. Quantum dots
K. Nanocrystalline materials
L. Others

2.2.3 Application

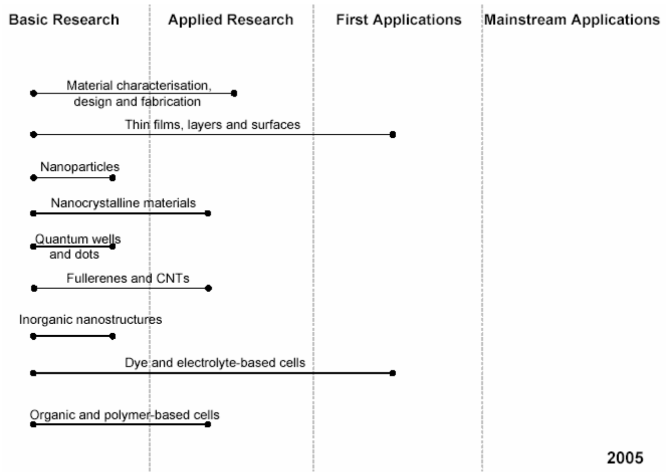
Expanding on this, experts were asked to identify the most important R&D topics to them and chart their progression over the next nine years, from basic R&D through to current applications. The definitions used for each stage in the development process are given below, and the charts describing this progression are on the following page:

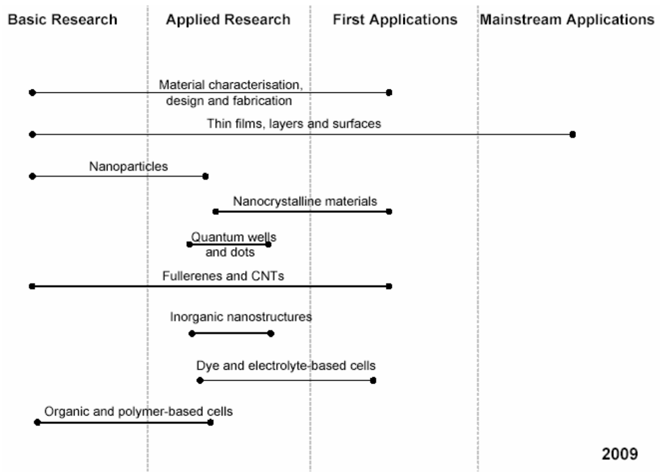
Basic R&D phase: applications in this phase have received the interest of one or more researchers in the world. Some applications might still be in early development, while others are tough to develop and need a lot of basic research to be understood. The object of basic R&D is to validate the original hypothesis. Various applications are currently in this phase.

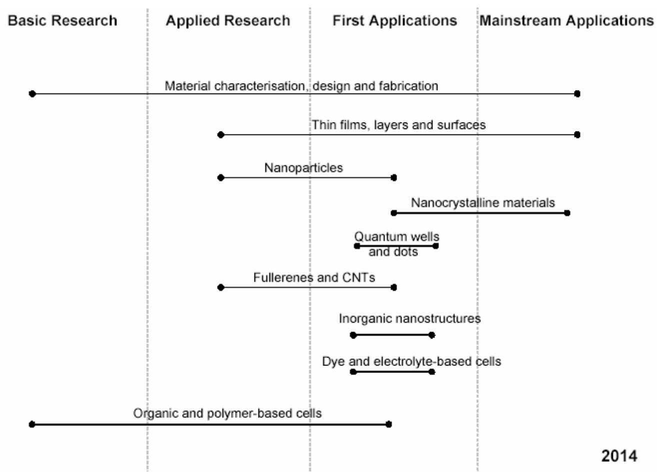
Applied R&D phase: after the hypothesis is validated, research typically (but not necessarily) moves from pure research labs to more commercial labs and companies. Applied R&D will eventually result in a proof of concept, a successful demonstration model. While the production issues might not have been solved yet, a successful prototype/model has been validated.

Product R&D phase (**first applications**): after demonstrator models and prototypes, initial, usually prohibitively expensive, small numbers of products may be produced. If these prove successful, companies will seek to enhance production to gain market share. Generally at some point, demand increases sufficiently to offset the investment needed to start production. This phase ends at a point when feasibility proven and production is to start.

Production level and incremental research (**mainstream applications**): the final development phase, when production has reached significant numbers and research focuses on incrementally improving the products.

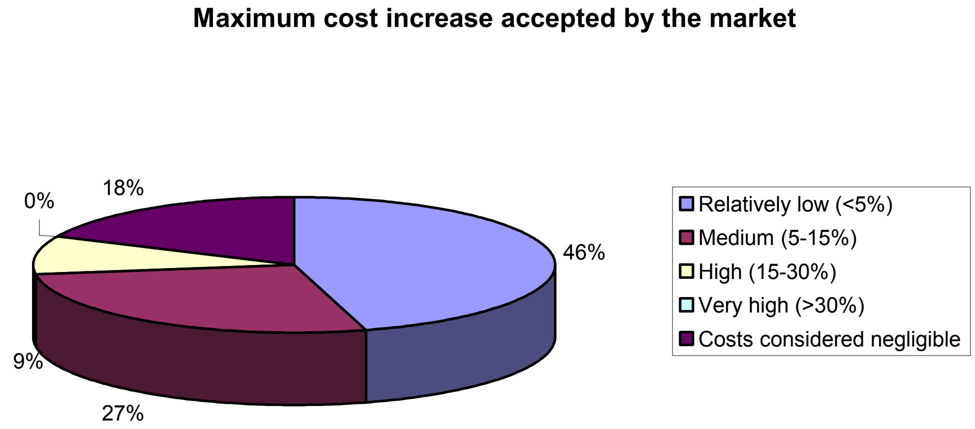






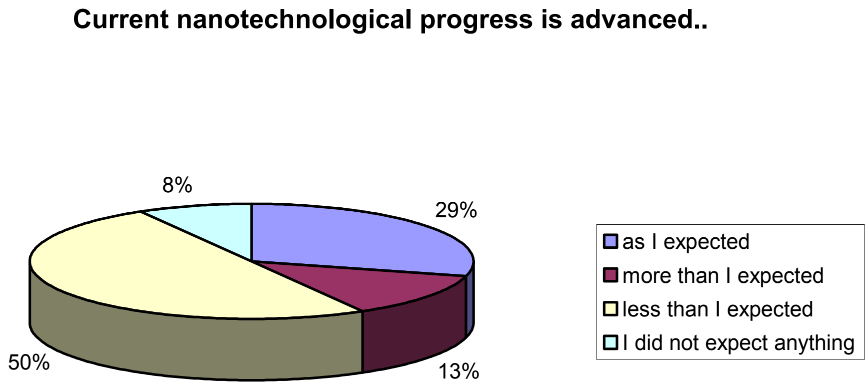
Material characterisation, design and fabrication will be an important area of basic research for the foreseeable future with higher photovoltaic efficiencies being a main goal followed by improving stability. The incorporation of these new materials into modules and printed cells is expected from 2009 onwards. Manufacturing issues include supply of materials, decreasing costs and ensuring environmentally sustainable production. Thin films are seen as the earliest mainstream application, however dye and electrolyte based cells are also seen as an early entrant to the market place (with small-scale first applications already in 2005).

Solar cell technology is well established so it is unsurprising that most experts believe that only a small or modest cost increase due to nanotechnological advances would be tolerated by the markets. Very high cost increases would not be accepted, however 19% of the experts thought that in some circumstances conventional approaches will not provide the necessary advances, and so the costs would be considered negligible when compared with the tremendous benefits associated.



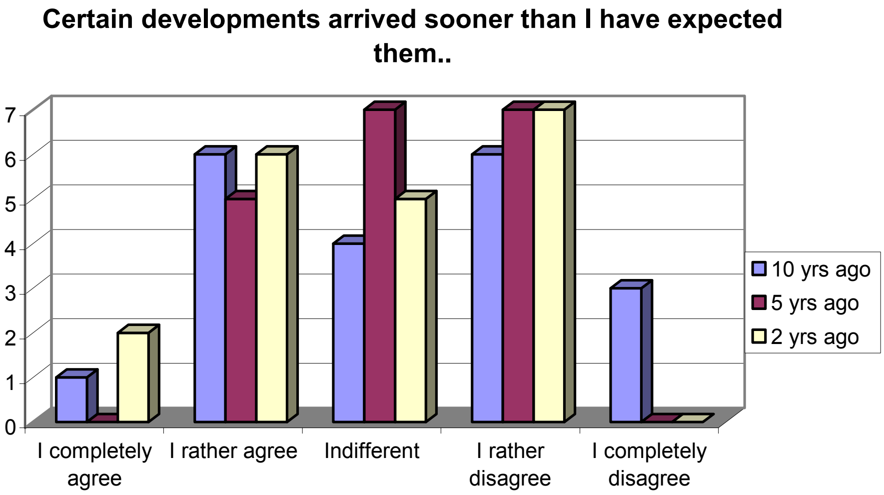
2.2.4 Retrospect

To place current and future R&D in perspective, experts were asked their opinion on how nanotechnologies had impacted on solar cell development over the past ten years. Half of the experts believe that the current nanotechnological progress of solar cells has advanced less than expected with a further 29% answering that it had developed as expected. Only three experts answered that it had progressed more than anticipated (see below).

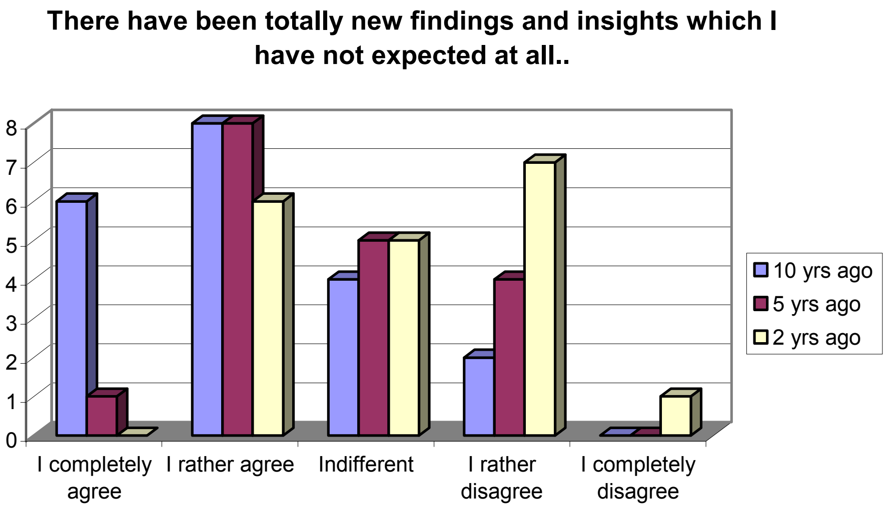


There is no overall consensus on whether nanotechnology contributions to solar cells have developed more quickly or slowly over the last ten years, which can be in part explained by the vast number of different materials being developed. However some specific developments have appeared earlier than expected such as dye-sensitized solar cells; nanostructured solar cells; carbon nanotubes; molecular modeling; advances and applications in chemical synthesis; ionic liquids (and their semi-solidification).

In contrast some developments did not occur as early as expected: solid organic electrolytes; charge separation/efficiency; high gas barrier films; air-stable polymers; efficient thin-film modules; commercially available nanotechnology-based solar cells.



The rate at which the field is advancing appears to be slowing, or at the least it is becoming easier to predict new findings and insights. This can be partly attributed to the fact that ten years ago many of the exotic materials being developed for solar cells (such as carbon nanotubes, quantum dots) had not long been identified and the primary focus was the elucidation of their novel properties through basic research, with little expectation of the breadth of application areas.



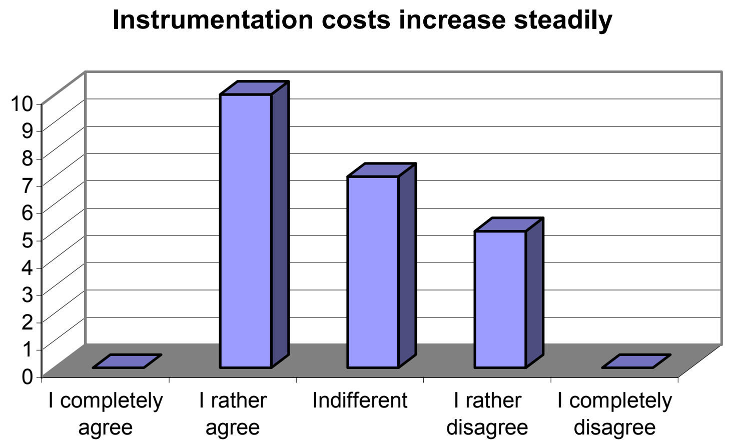
Some of the specific new findings that were unforeseen include:

- Quantum dot based solar cells
- bandgap modification by controlling nanoparticle size
- higher efficiencies in a variety of technologies
- nanocomposite solar cells (organic)
- tandem stack thin-film cells of amorphous and nanocrystalline silicon
- low temperature prepared nanocrystalline photoanodes
- optical enhancement through designed nanoparticles

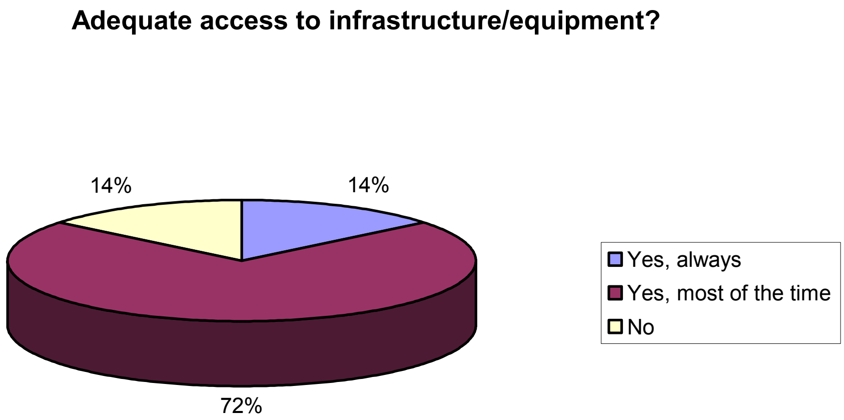
2.3 Non Technological Aspects

2.3.1 Infrastructure Requirements

Experts were asked whether the instrumentation costs for the manufacturing, characterization and manipulation of nanotechnologies in the application(s) areas of solar cells have increased steadily. Ten respondents thought that costs had increased compared with five who did not. A further seven were indifferent.



Access to infrastructure/equipment for the performance of typical nanotechnology-related activities (this includes the use of both their own and external facilities through existing collaboration) does not appear to be an issue for most experts (86%) answered that they had adequate access most or all of the time.

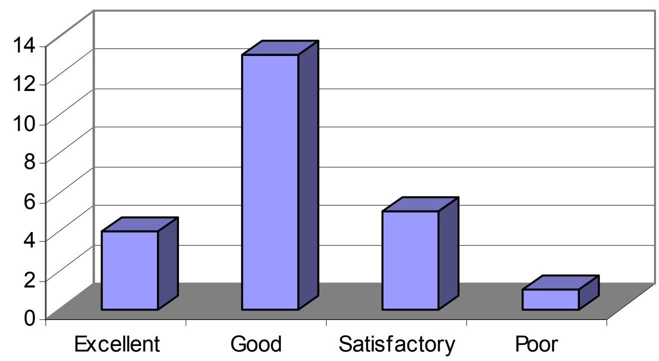


2.3.2 Economic Aspects

Growth in the solar cell market is accelerating, with 64% increase in installations from 2003 to 2004 compared with a 32% increase the preceding year.[2] This effectively is a doubling of the market between 2000 and 2003, and is equivalent to approximately 5% of the global energy market in 2003.[1] The market leaders in terms of megawatts of installation are Germany, followed by Japan and then the US. Globally the revenues from solar energy are estimated at 3 to 4 billion USD. The market leaders in manufacturing solar cells are Sharp, Kyocera, BP Solar and Shell Solar, and take over 50% of the market share.[1]

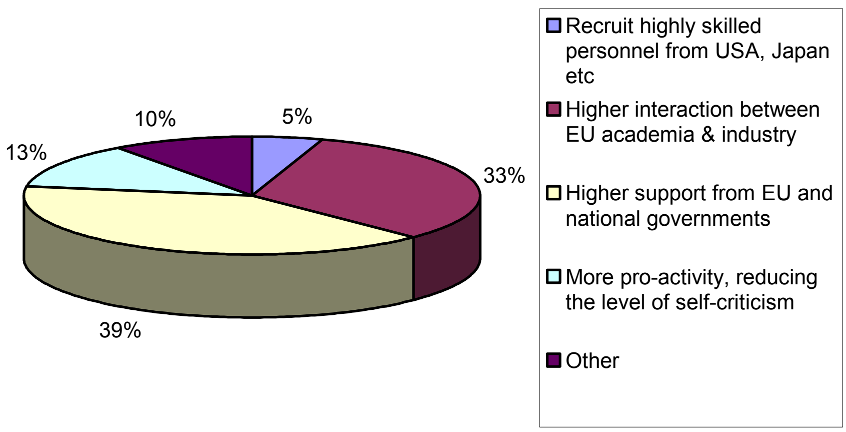
Basic research in nanotechnology application in solar cells in Europe is generally seen to compare well with other world regions, with only one expert thinking that Europe was relatively poor to other world regions. Experts were asked how the European Commission could contribute most to advancing state-of-the-art nanotechnology in their application areas. Twenty-two experts said this could be achieved by supporting more, smaller collaborative R&D projects rather than fewer, bigger collaborative R&D projects (one expert). Specifically this would allow more flexible, basic R&D including increased material discovery (with optimization a future objective).

Relative position of European nanoscience in your application area of solar cells compared to other regions

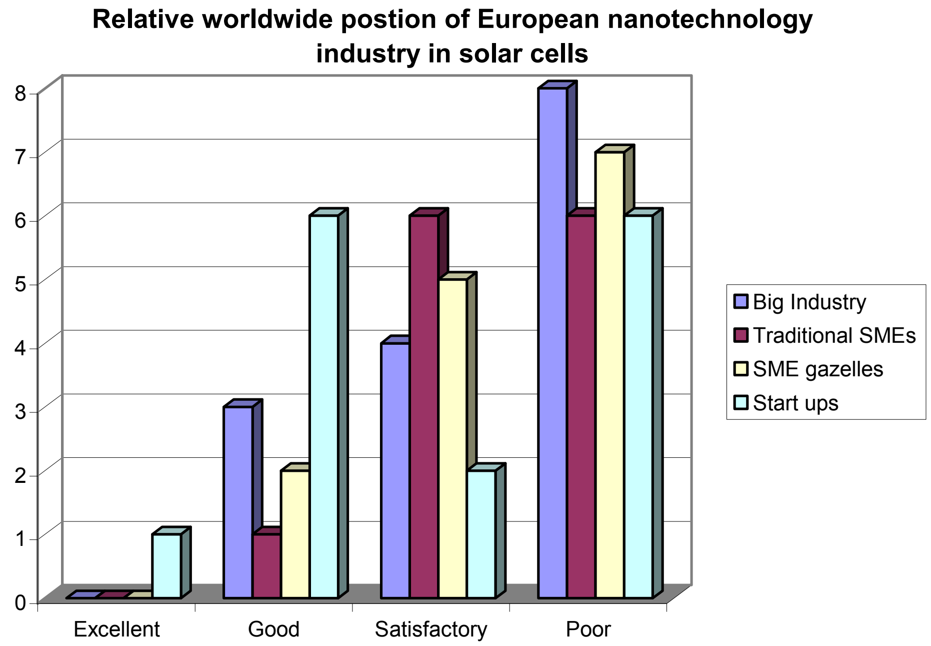


To ensure that European nanotechnology R&D continues to meet the demand of this burgeoning market, the two most important factors during the next decade will be higher support from the EU and national governments, and higher interaction between EU academia and industry. In contrast recruiting skilled personnel from other regions is seen as relatively unimportant. Other aspects that may need to be addressed include the reorganisation of funding structures, mechanisms to retain skilled EU researchers, increasing the strength of the industrial base, and providing high risk investment (see graph below).

Most important factors for the growth of European nanotechnology in solar cells R&D



This will be essential to reverse the opinion that European nanotechnology industry is relatively poor compared with other regions (in particular large companies). In fact, when asked to identify the top three to five industrial players worldwide who are contributing the most to advancing nanotechnology in solar cells, several European companies were cited by experts, however the majority were located in the USA or Japan.



Region	**Company (number of citations by experts)**
Europe	Solaronix (2), Siemens, Hydrogen Solar, Philips, NTera
N. America	Konarka (4), Kodak, Nanergy
Asia	Aisin Seiki (2), Fuji, Kaneka, Canon, Fujikura, Sony

2.4 Conclusions

European nanoscience in the area of solar cells at present is in a healthy position relative to the rest of the world. What is lacking is the effective industrial application of this research, with European industry seen as poor at every level compared with other regions. Many of the leading companies described by the experts are based in the USA or Japan. According to a large number of experts, innovation is driven almost exclusively by academic research, with low interaction between academia and industry, as evidenced by thirteen expert recommendations that this should be strengthened. This will be a major bottleneck with half of the experts of the opinion that nanotechnology development in solar cells has not advanced as fast as they thought it would.

According to the experts, within the next ten years the major nanotechnological challenges in solar cells development will include:

- reducing costs of both the fabrication process and the final product
- increasing reliability
- increasing efficiency of fabrication process and product
- increasing lifetime

And more specifically:

- development of innovative light trapping structures
- obtaining and stabilizing nanoparticle concentration at >60%
- new techniques to form active layers in thin film solar cells
- more work into the potential of implementing nanotechnology into inorganic solar cells

Nanotechnology is expected to play a major role in solar cell R&D by 2014, primarily by increasing efficiencies and by reducing costs. The applications will be from ubiquitous and cheap solar cells for use in low-power remote applications (e.g. RFID tags) to higher power applications suitable for domestic energy needs in remote communities. As such, the technologies vary from increasing the efficiency of e.g. monocrystalline silicon cells through the application of thin films (or new materials) through to the decreased cost and increased durability of flexible thin-film and organic-dye based solar cells.

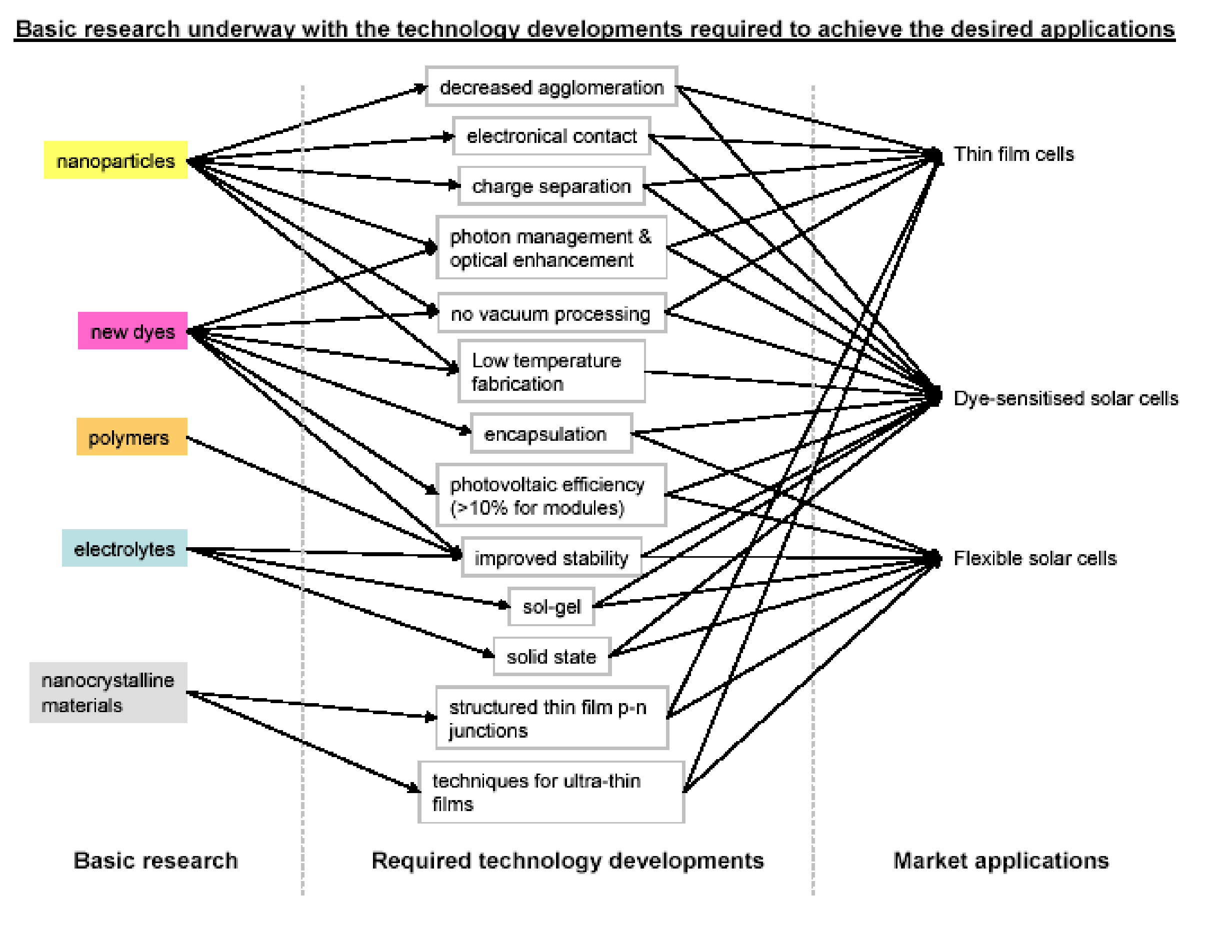
At present, the nanotechnology impact on solar cells is seen by experts as still in the basic research phase with much research required in new material identification and development to improve efficiencies of energy conversion and stability/durability of active components of solar cells. In terms of time-lines increasing efficiency is seen as paramount followed by improving stability, and lastly by decreasing the costs of manufacturing these materials. Thin-films are seen as the most promising area for solar cells (all but two experts selected this category) and throughout the next four years the focus will be on basic and applied research with first applications expected in thin-films by 2009, and these to be well established by 2014. Thin-film applications are expected to be followed closely by dye-based solar cells and those incorporating nanocrystalline materials, with other technologies including Quantum dots, fullerenes and carbon nanotubes not expected to have applications until 2014.

One barrier to exploitation will be sourcing nanoparticles and other nanomaterials for solar cell applications. Currently the majority of nanoparticles used by experts in their R&D applications are made in-house, or from other colleagues or public research organizations, only 21% come from an industrial supplier. This may bring its own hurdles if scaled-up production of the raw materials must be accomplished before the solar cell itself can be manufactured. This journey could be made easier though closer collaboration with industry- the industrial partner being tasked with the manufacture of raw materials for the application.

This collaboration will be necessary early on if another of the criteria deemed important by the experts is to be met. Solar cell technologies will only be accepted by consumers if the cost increases are relatively low compared with existing technologies. To ensure this cost-effective, mass-production of components must be achieved which necessitates early involvement of industrial partners.

Achieving these goals of identifying more efficient photovoltaic materials and developing these into robust and cost-effective platforms would require funding of more smaller, collaborative projects- to maximise diversity.

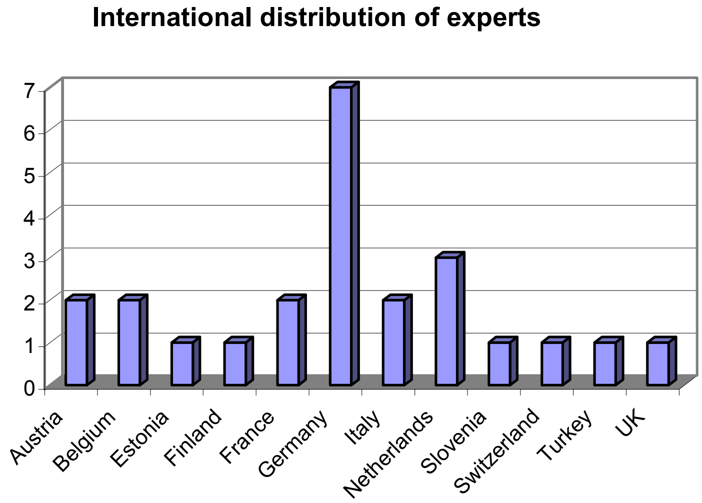
Recommendations for specific areas with required technology developments are summarised in the diagram below.



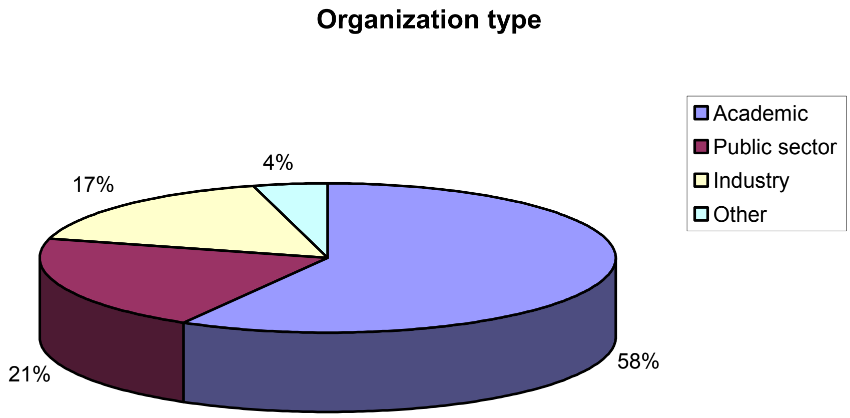
Appendix

Statistics

Within the topic of solar cells over 45 experts were asked to take part in the questionnaire of which 24 completed and returned the questionnaire. The international distribution of experts is shown in the graph below.



The types of organization represented by those experts completing the questionnaire were Academic, Public Sector, Industry and Other. Academics represented the largest group of recipients at 58% as can be seen in the pie chart below. Those who selected the "Other" category were from the Fraunhofer Institutes in Germany which are non-governmental and non-profit.



List of experts

Prof. Gilles Dennler, LInz Institute for Organic Solar Cells, Austria	Prof. Dieter Meissner, FH Wels, Austria	Robert Mertens, Senior Vice President, IMEC, Belgium
Dr. Guido Agostinelli, Senior Research Scientist, IMEC, Belgium	Prof. Enn Mellinov, Tallin University of Technology, Estonia	Prof. Helge Lemmetyinen, Inst. Materials Chem. TUT, Finland
Dr. Ramon Tena-Zaera, Senior Researcher, LCMTR-CNRS, France	Claude Jaussaud, Engineer, CEA, France	Prof. Walther Fuhs, Hahn-Meitner Institut Berlin, Germany
Dr. Volker Sittinger, Senior Researcher, Fraunhofer IST, Germany	Bernhard Dimmler, Wuerth Solar, Germany	Karl-Heinz Haas, Deputy Director, Fraunhofer-Institut für Silicatforschung, Germany
Prof. Bernd Spangenberg, Head of Nanotechnology dept., IHT Aachen University, Germany	Prof. Dieter Wöhrle, Head of Institut for Organic and Macromolecular Chemistry, University of Bremen, Germany	Dr. Uwe König, Head of NanoEnergie, Zentrum für Brennsoffzellentechnik GmbH, Germany
Pietro Perlo, Director, Centro Ricerche Fiat, Italy	Robert Edwards, EC-DG JRC, Italy	Hubert Veringa, Unit Manager, Energy Research Centre, The Netherlands
Prof. Joop Schoonman, TU Delft, The Netherlands	Prof. Jatindra Kumar Rath, Utrecht University, SID-Physics of Devices, The Netherlands	Prof. Boris Orel, Head of Dept., National Institute of Chemistry, Slovenia
Toby Meyer, CEO Solaronix SA, Switzerland	Baha Kuban, Gen. Secretary Bus. Develop., EUROSOLAR TURKEY, Turkey	Nigel Mason, Manager, Future Technology, BP Solar, UK

References

[1] Solar Generation (EPIA) 2005, http://www.epia.org/05Publications/EPIAPublications.htm

[2] MARKETBUZZ 2005: Annual world solar photovoltaic (PV) market report.

NanoRoadMap is a project co-funded by the 6th Framework Programme of the EC

Draft RoadMap on Thermoelectricity

The Institute of Nanotechnology

October 2005

Partners

1. Introduction

1.1 Background

The NanoRoadMap (NRM) project, co-funded by the European Commission (EC), is aimed at road-mapping nanotechnology related applications in three different areas:

- Materials
- Health & Medical Systems
- Energy

Within the project, an international consortium consisting of eight partners covering eight European countries and Israel, has joined forces to cover the time-frame for technological development in this field up to 2014. The results of the NRM project are to be used by any European entity interested in planning an R&D strategy taking into account nanotechnology. An important potential user is of course the EC itself in the preparation of the 7th Framework Programme (FP7) for research and technology development. For additional information on the NRM project, please refer to www.nanoroadmap.it

1.2 Goals

The primary objective of NRM is to provide coherent scenarios and technology roadmaps that could help the European players to optimize the positive impact of nanotechnology on society, giving the necessary knowledge on its future development and when technologies and applications will come into full fruition.

The key users of the reports are mainly European SMEs, research organizations, public bodies in general and the EC in particular. Even though a special focus is put on SMEs, these roadmaps are also meant to be useful for larger corporations.

This report is one of the three final deliverables of the NRM project and it is aimed at providing a thorough overview of specific topics selected for road mapping within the field.

1.3 Methodology

1.3.1 Collection and synthesis of relevant existing information

In October 2004 three sectoral reports were published, each covering one of the above mentioned areas. They were based on the collection and synthesis of existing public sources in 31 countries and were published as key input for the celebration of the First NRM International Conference held in Rome the 4th – 5th of November 2004. The full report can be downloaded for free on the project web site.

The report within the energy sector focused on reviewing the different aspects of nanotechnology in 10 topics, giving its definition, describing its most remarkable properties, current and future markets and applications, and leading countries and highlighted R&D activities in the field. A general review of non technological aspects (social, legal, ethical and health and safety aspects, but also economical aspects and infrastructures requirements) was also performed.

The 10 topics identified, even not being completely homogenous in terms of scope or classification, were intended to adequately cover the field of energy. The following list was agreed upon the different partners of the NRM project (similar classifications can be found in the existing bibliography):

- Solar cells
- Fuel cells
- Thermoelectricity
- Rechargeable batteries
- Hydrogen storage
- Supercapacitors
- Insulation
- Glazing Technology for Insulation
- More efficient lighting
- Combustion

1.3.2 Selection of Topics

Another major goal of that report was to set the basis for discussion and selection for road mapping of 4 out of the 10 topics identified above. A preliminary selection of topics was presented during the First International Conference in November, 2004.

After a thorough discussion, which involved international experts in the field of nanotechnology, four topics were selected (and validated in dialogue with the European Commission). The subjects were partly combined with each other, leading to the four chosen topics:

- Solar cells
- Thermoelectricity
- Rechargeable Batteries and Supercapacitors
- Heat Insulation and Conduction

1.3.3 Roadmaps elaboration

One draft roadmap will be prepared for each of the four aforementioned topics. Their preparation and execution will be based upon a Delphi-like approach. The methodology consists of 2 cycles, which is the same for the four topics. The Delphi exercise consists in:

- Selecting top-international experts on the field
- Preparing a dedicated questionnaire for each of the topic to be road mapped
- Circulating the questionnaires and gathering experts' responses (1st cycle)
- Preparing a first summary of the given answers
- Circulating the summary and partly interpreted data, asking for feedback (2nd cycle)
- Elaborating the roadmap

Through one international and eight national conferences these reports will be proposed to the interested partners and comments collected so as to build up final definitive roadmap.

2. Road Map on Thermoelectricity

2.1 Definition of thermoelectricity

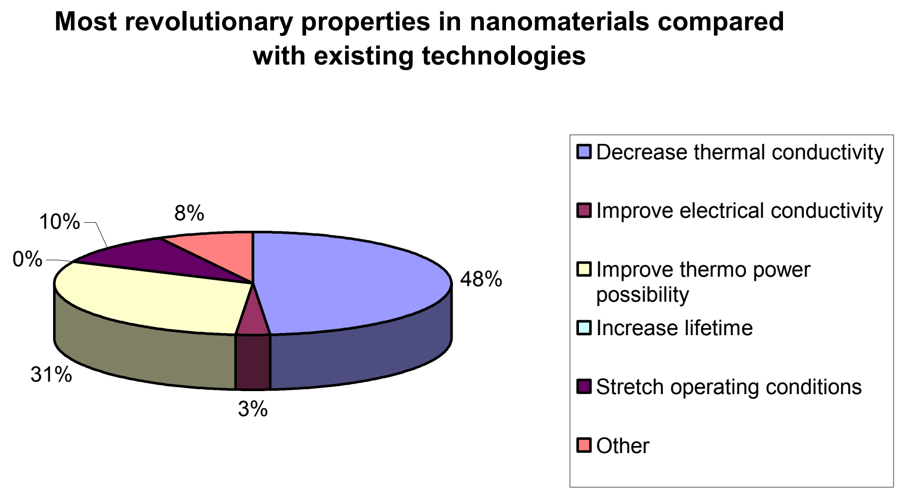
Thermoelectricity is the conversion of heat to electricity or vice versa, also known as the Peltier-Seebeck effect. Thermoelectric (TE) devices are solid-state systems that can provide cooling, heating, precise temperature control, and also can convert heat into electricity. In the future it should be possible to turn an automobile's waste heat into electricity, e.g. to run the air conditioner. In other applications tiny dots of thermoelectric materials could be applied to the surface of microprocessor chips to aid localised cooling, that would be more efficient than merely using a fan, and would therefore allow the processor to run at a faster speed. Also telecommunications routers based on fast fibre-optic switches could be operated at lower voltage, which means, that more switches could be packed into a smaller space.

The technology works by taking advantage of semiconductor materials with different thermal conductivities. When two such materials are electrically connected and placed in a thermal gradient, electrical current will flow from one to the other. The materials best suited for thermoelectric applications should have high Seebeck coefficients (which is defined by the ratio of the applied voltage difference V and temperature difference T). The dependence of device efficiency for material properties is expressed by the dimensionless thermoelectric figure of merit, ZT, where T is the operating temperature and Z is proportional to the Seebeck coefficient, the electrical conductivity and reciprocal to the thermal conductivity.

2.2 Scientific and Technological Aspects

A good thermoelectric material must have a large Seebeck coefficient, S, to produce the required voltage, a high electrical conductivity, s, to reduce the thermal noise (joule heating), and a low thermal conductivity, k, to decrease thermal losses from the thermocouple junctions. The best TE materials at present have ZT values of approximately 1, which presents a bottleneck in wide-scale application. Nanotechnology offers a solution to this as thermal conductivity (k) values decrease in nanostructured materials (due however to the increased surface to volume ratio). Theoretically nanostructured materials and nanoparticles offer potential ZT values of 3 or 4.

Unsurprisingly then, most experts believe that the most revolutionary properties of nanoparticles in thermoelectricity compared to existing/alternative technologies are their ability to decrease thermal conductivity and improve the thermo power possibility (see below).



Different types of structures have applications in thermoelectricity, primarily through decreasing thermal conduction and these are described below:

Nanocrystalline materials

These have highly defined lattices of small crystal diameter, which can aid in decreasing thermal conduction. They are usually deposited as thin films (up to 1μm thick). Examples of materials include Bismuth Telluride (BiTe) and Antimony Telluride (SbTe).

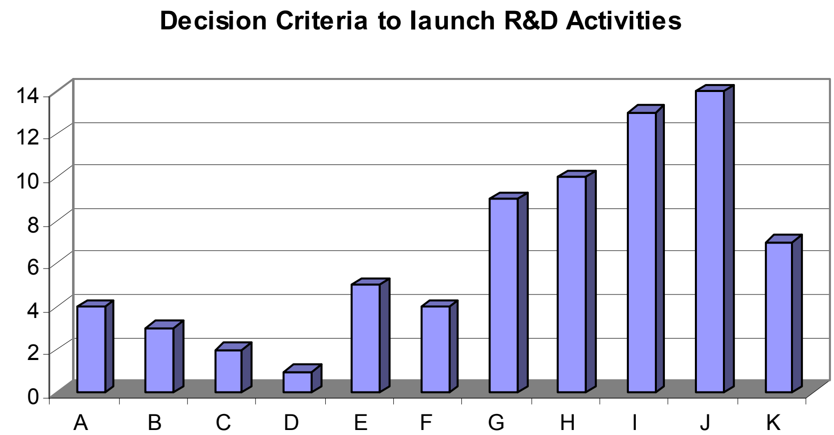
Nanoparticles and Nanowires

Due to the larger surface area these structures offer increased ZT values over layers and have potential applications in micro-coolers and generators.

Superlattices

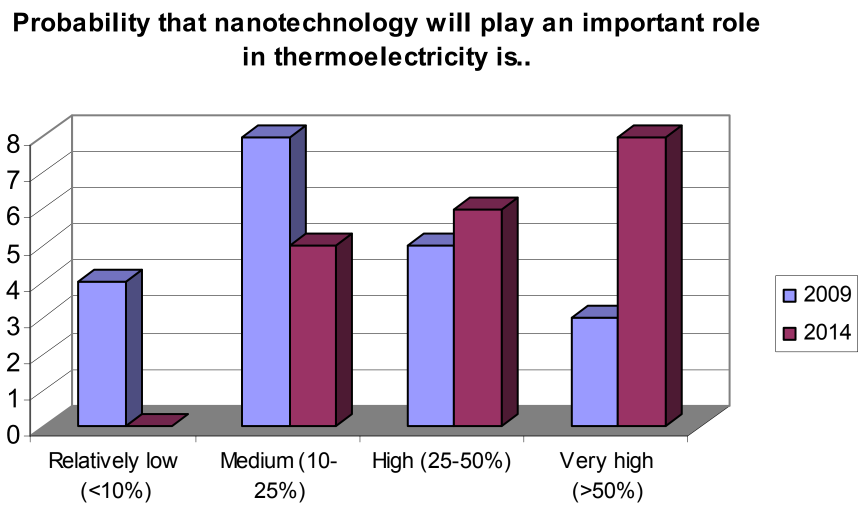
Consist of several alternating layers of ultra-thin films (few nm wide) of different materials. These have the effect of reducing thermal conduction without affecting electrical conduction. The identification and development of these materials was pioneered at the Research Triangle Institute, US.

Academic scientists make up 81% of the respondents to the Delphi questionnaire; so it is perhaps unsurprising that scientific reputation and publications rank high on the list of decision criteria to launch R&D activity (for example the three industrial experts chose market entry (E) and (F) and not publications). However, given that established thermoelectric devices are relatively inefficient and the means to redress this is through the development of new materials and structures, then it would be expected that most of the current R&D activities will be at the level of fundamental science.



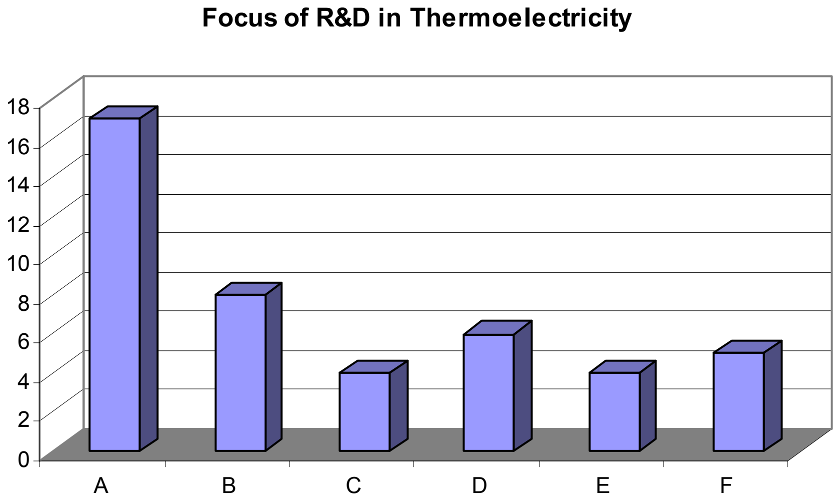
A. Low costs of the estimated product
B. Low costs of research process
C. Short time to market
D. Rapid readiness for start of production/product maturity
E. Specific market entry
F. Broad market entry
G. Possibility of governmental subsidy
H. Possible patent announcements
I. Scientific reputation
J. Possible publications in scientific journals of high reputation
K. Other

Nanotechnology however is expected to play an increasingly important role in thermoelectricity applications over the next nine years, presumably through the development of materials with lower k values and hence higher ZT values, thus improving efficiencies.



2.2.1 Basic Science

Most of the experts questioned focused their R&D activities in a few areas, with the most prominent area involving the generation of electrical current from “waste” heat sources. However, managing waste heat was also an important area of activity, as were high cooling systems and refrigeration at low temperatures (4 entries). Micro-generators and generators for space use were also mentioned.

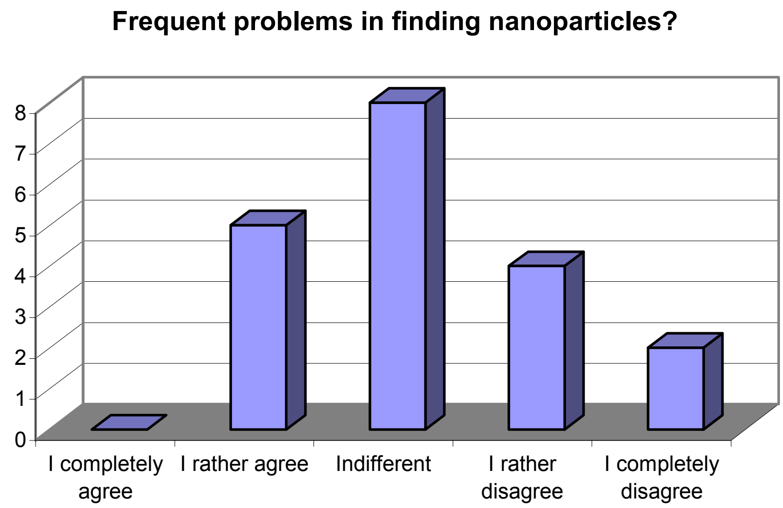


A. Generating electrical current from “waste” heat sources
B. Managing “waste” heat by transferring it to electrical current
C. Reducing power consumption of sensors, chips etc.
D. Improving reliability for electric energy generation, energy management
E. Developing thermal sensing
F. Other

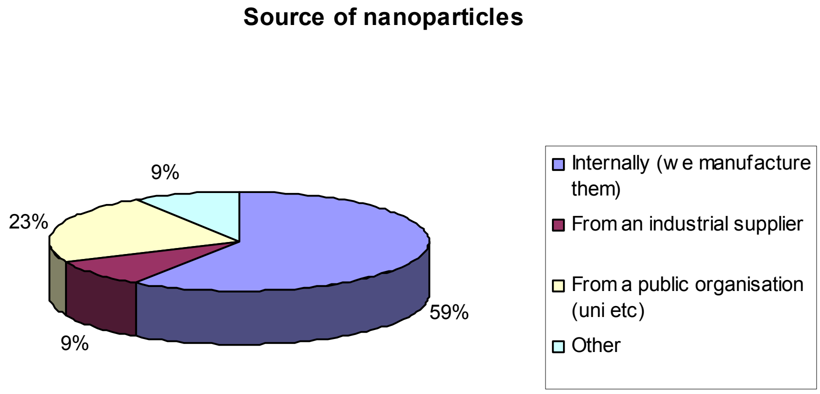
2.2.2 Nanotechnologies in Thermoelectricity – Value Chain

Production

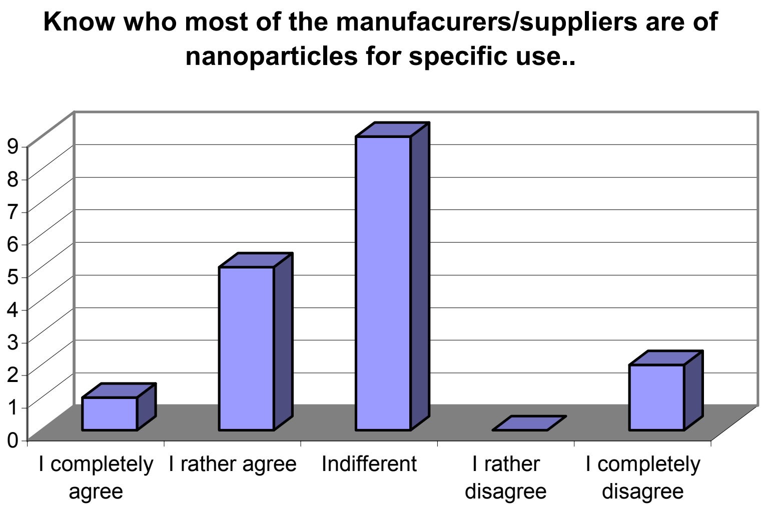
Most experts answered that they have little difficulty (29%) or no strong feelings (38%) regarding their ability to source nanoparticles for their R&D. 5 experts (or 24%) rather agreed that they have frequent problems in finding nanoparticles to satisfy their R&D and/or manufacturing needs.



The lack of difficulty in finding nanoparticles for R&D is probably because most experts make their own with only two sourcing them from industrial suppliers (in addition to internal supplies). Those who did not manufacture their own sourced them from collaborators or other public organisations. This can be explained by the fact that current efforts are mainly towards the identification and development of new materials, rather than their integration into devices.

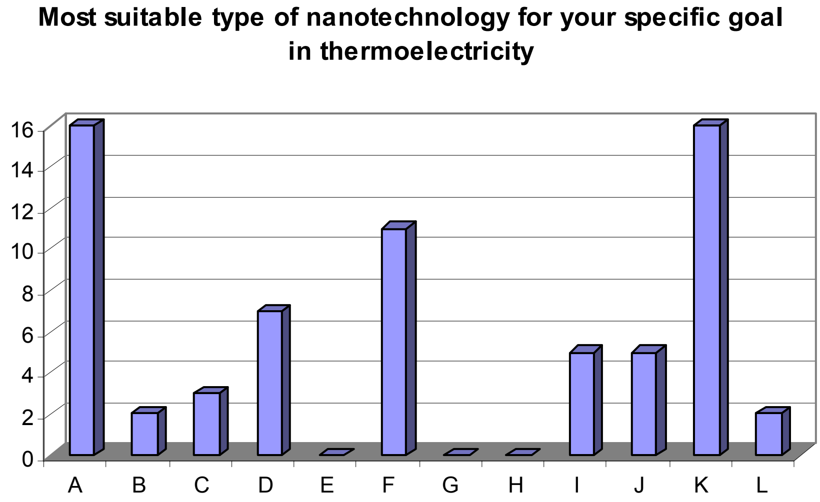


As a result of this only two experts felt that they did not know who most of the manufacturers/suppliers were for nanoparticles for their applications.



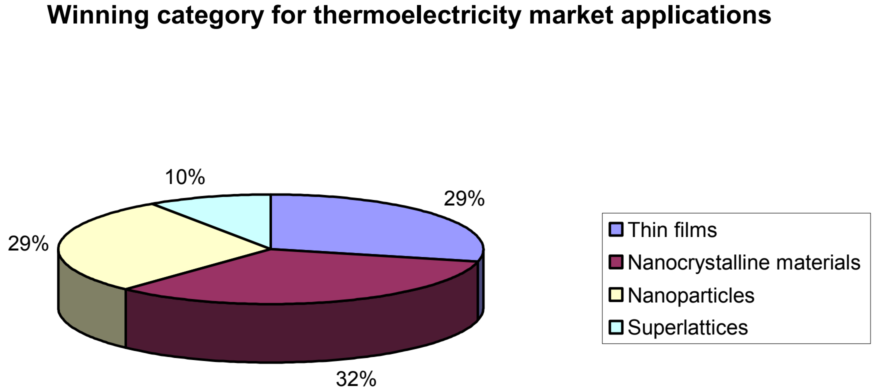
Functionalisation

Thin films, layers and surfaces, and nanocrystalline materials, followed by nanoparticles, are the types of nanotechnologies used most extensively by our experts in their thermoelectricity work. The "Other" category included superlattices and nanocomposites.



A. Thin films, layers and surfaces
B. Carbon nanotubes
C. Inorganic nanotubes
D. Nanowires
E. Biopolymers
F. Nanoparticles
G. Fullerenes
H. Dendrimers
I. Quantum wells
J. Quantum dots
K. Nanocrystalline materials
L. Others

Four areas were identified as winning categories of nanotechnology for thermoelectricity market applications (see below).



2.2.3 Application

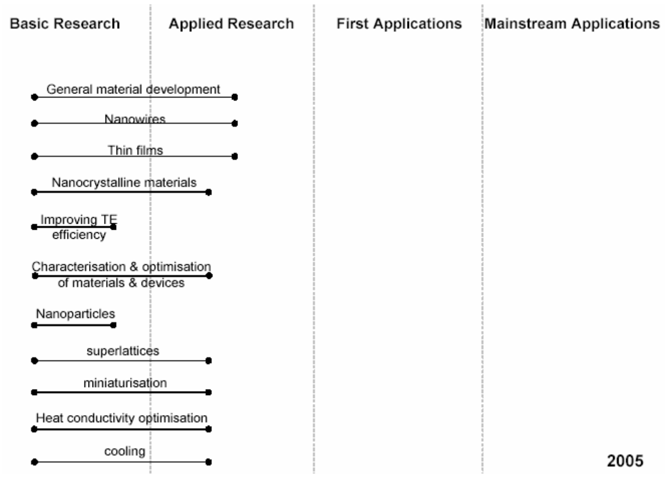
Expanding on this, experts were asked to identify the most important R&D topics to them and chart their progression over the next nine years, from basic R&D through to current applications. The definitions used for each stage in the development process are given below, and the charts describing this progression are on the following page:

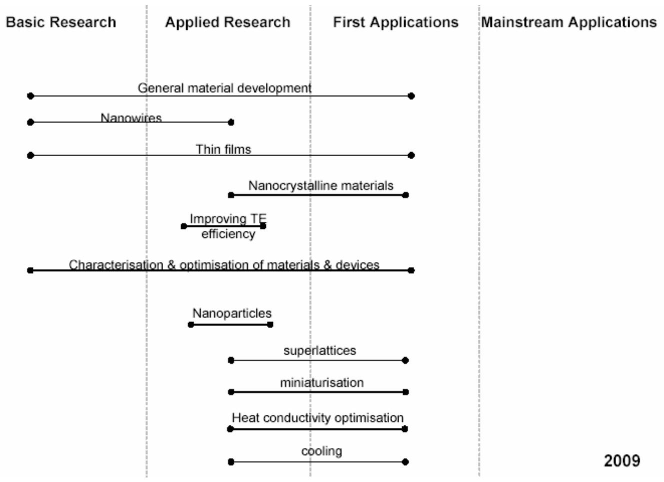
Basic R&D phase: applications in this phase have received the interest of one or more researchers in the world. Some applications might still be in early development, while others are tough to develop and need a lot of basic research to be understood. The object of basic R&D is to validate the original hypothesis. Various applications are currently in this phase.

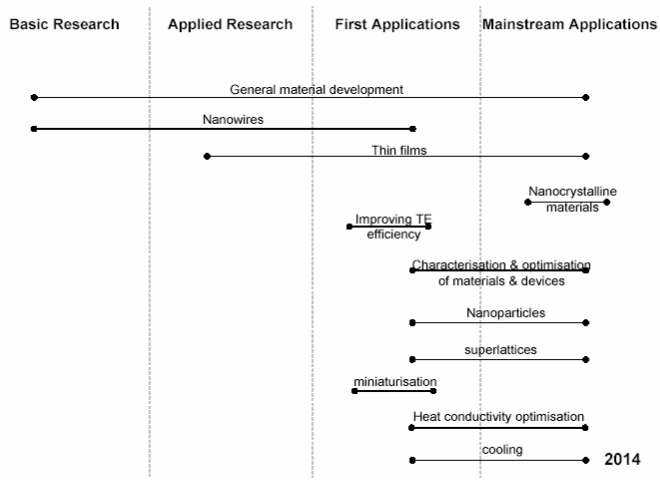
Applied R&D phase: after the hypothesis is validated, research typically (but not necessarily) moves from pure research labs to more commercial labs and companies. Applied R&D will eventually result in a proof of concept, a successful demonstration model. While the production issues might not have been solved yet, a successful prototype/model has been validated.

Product R&D phase (**first applications**): after demonstrator models and prototypes, initial, usually prohibitively expensive, small numbers of products may be produced. If these prove successful, companies will seek to enhanceproduction to gain market share. Generally at some point, demand increases sufficiently to offset the investment needed to start production. This phase ends at a point when feasibility proven and production is to start.

Production level and incremental research (**mainstream applications**): the final development phase, when production has reached significant numbers and research focuses on incrementally improving the products.



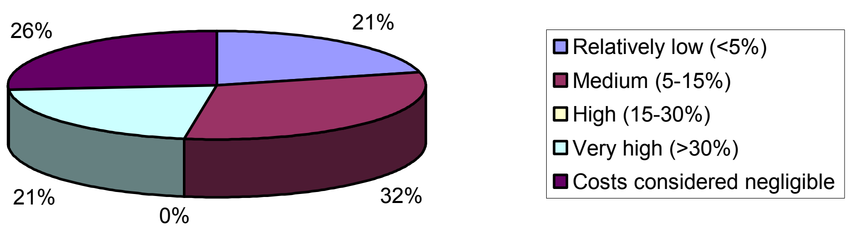




The common theme for important R&D topics over the next 9 years is the development of new materials. These include thin films, nanoparticles, nanocrystalline materials, nanowires and superlattices, but also specific families of materials such as skutterudites and clathrates were mentioned. As described earlier much of this work focuses on lowering heat conductivity and thus improving the thermoelectric efficiency. However research into new materials aimed at cooling applications were also cited. The first applications will most probably be in vehicles (converting waste engine heat to electricity) and in microelectronics, as early as 2014.

Opinion was divided when asked about the maximum cost increase that would be accepted by the market due to the advantages introduced by new nanomaterials. 53% answered that only a relatively low or medium increase would be tolerated, while 21% thought that very high cost increases would be tolerated, and a further 26% believed that as no conventional approach exists, the costs would be considered negligible when compared with the tremendous benefits associated.

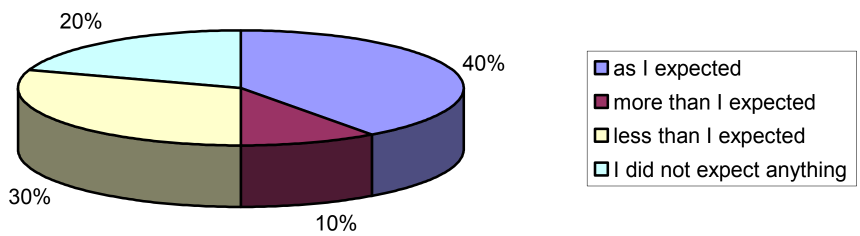
Maximum cost increase accepted by the market



2.2.4 Retrospect

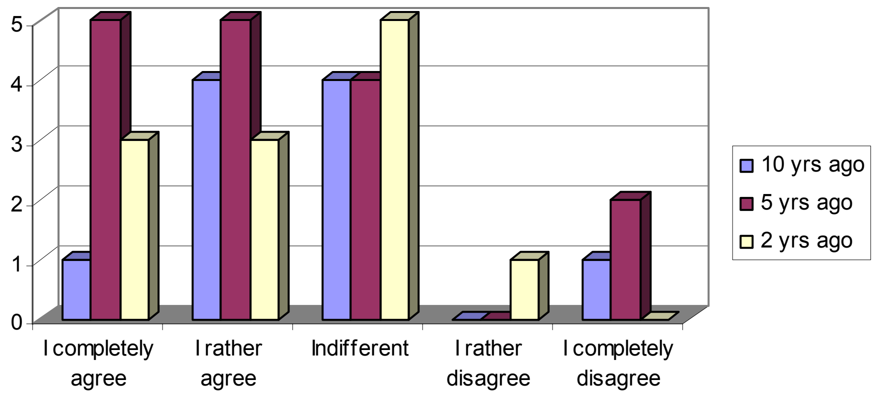
To place current and future R&D in perspective, experts were asked their opinion on how nanotechnologies had impacted thermoelectricity R&D over the past ten years. 50% of experts were of the opinion that the current nanotechnological progress in thermoelectricity applications has advanced as expected or more than expected, while 30% believed it to have progressed less than expected.

Current nanotechnological progress is advanced..



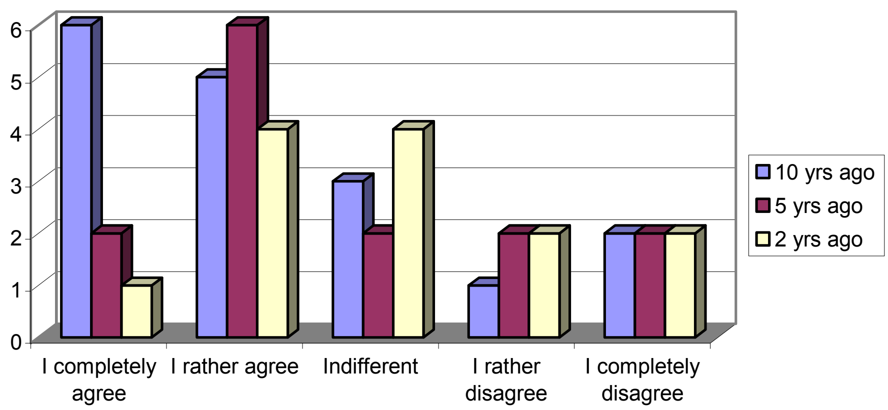
However experts were clearer about the speed with which developments have occurred in this sector over the past ten years, with specific examples of those that have appeared earlier than anticipated including multilayers and superlattices of semiconductors, enhancement of thermoelectric performances, clathrates, and use of Quantum Dots appearing much earlier than expected.

Certain developments arrived sooner than I have expected them..



When asked about unexpected new findings and insights the majority of experts agreed that this had been the case ten years ago, and to a lesser extent five and two years ago. Specific examples included the identification of new families of materials, boundary conditions influencing the thermoelectric power, theoretical prediction of ZT increase for nanostructured materials, low dimensional effects on electron transport, effects of nanoparticles on heat transport, phonon glass and electron crystal (PGEC).

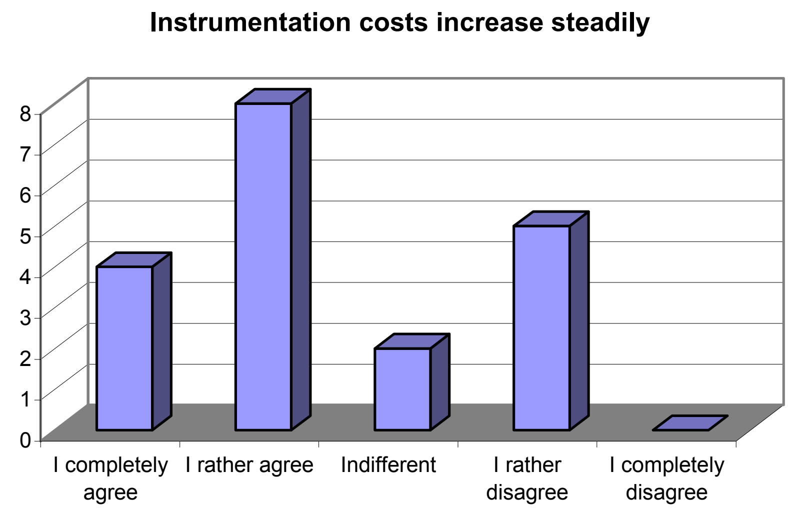
There have been totally new findings and insights which I have not expected at all..



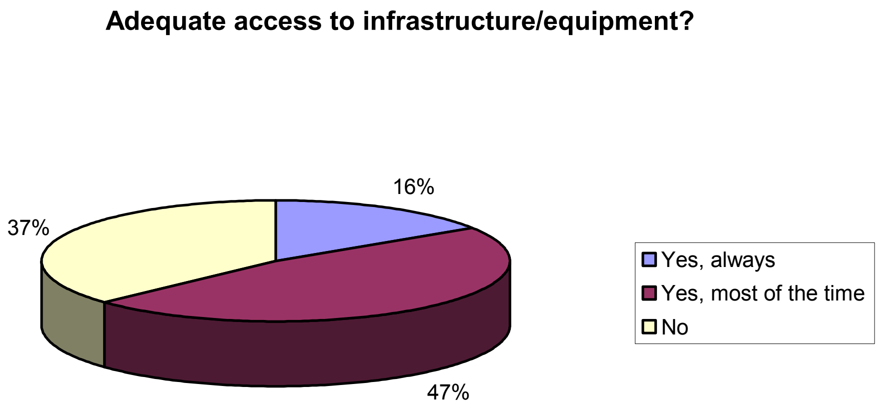
2.3 Non Technological Aspects

2.3.1 Infrastructure Requirements

Experts were asked whether the instrumentation costs for the manufacturing, characterization and manipulation of nanotechnologies in the application(s) areas of thermoelectricity have increased steadily. Twelve respondents thought that costs had increased compared with five who did not. A further two were indifferent.



The next question asked experts whether they had adequate access to infrastructure/ equipment for the performance of typical nanotechnology-related activities (this includes the use of both their own and external facilities through existing collaboration). 63% answered that they had adequate access most or all of the time, however the remaining 37% felt that they did not.

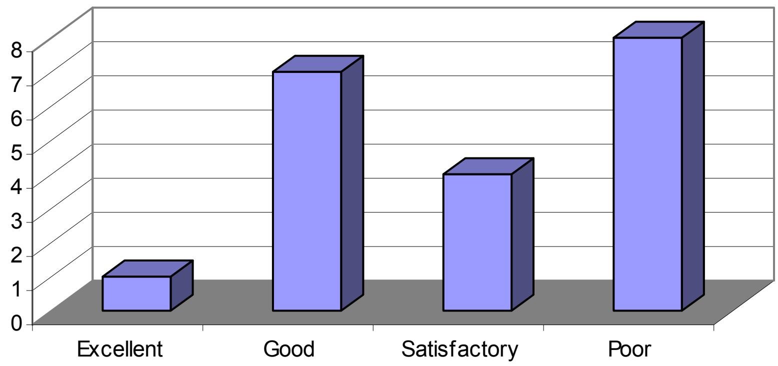


2.3.2 Economic Aspects

Although thermoelectric devices have been on the market for several decades, the limiting factor has always been low efficiency. Nanotechnology advances directly address this issue by providing materials with higher efficiencies for thermoelectric generators and cooling devices. However at present there is limited market applications with the main effort in basic and applied research into novel materials, understanding their properties and developing the tools and fabrication processes for their routine manufacture.

With this in mind it is important to determine the current status of European nanoscience relative to the rest of the world. When asked to compare the relative position of European nanoscience in their application area of thermoelectricity with other regions such as the USA and SE Asia, the results were mixed with eight experts stating that Europe was good or excellent, and eight stating it was poor. A further four thought that European nanoscience was satisfactory compared with other regions.

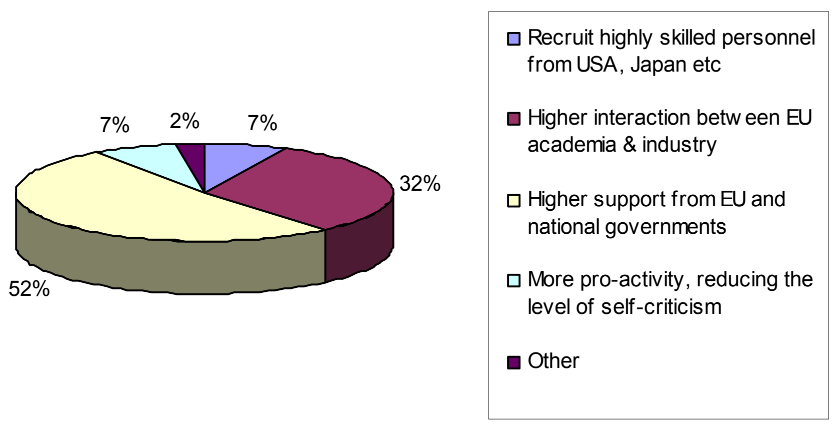
Relative position of European nanoscience in your application area of thermoelectricity compared to other regions



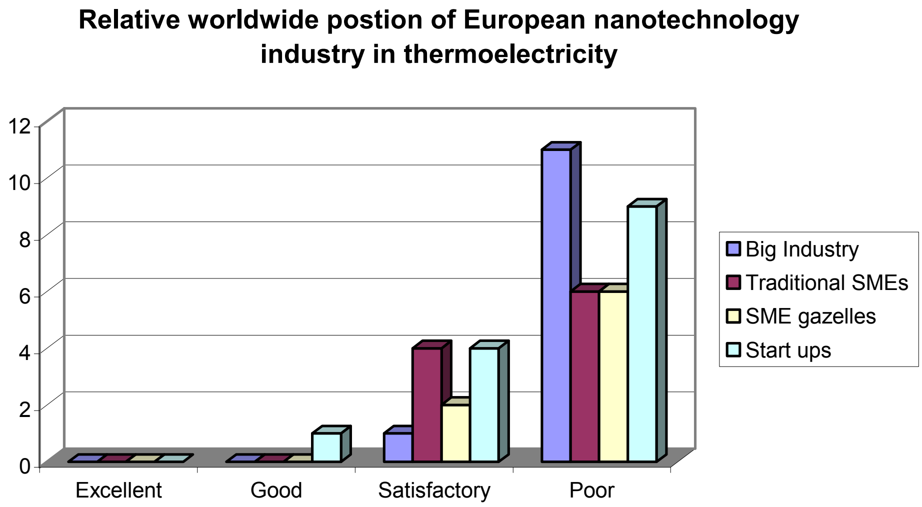
Experts were asked how the European Commission could contribute most to advancing state-of-the-art nanotechnology in their application areas. Seventeen experts said this could be achieved by supporting more, smaller collaborative R&D projects rather than fewer, bigger collaborative R&D projects (four experts). Specifically this would allow stronger collaborations between groups, and a wider range of more focused and targeted R&D with increased competitiveness and productivity. One expert stated that both types of project were needed.

According to the experts, the two most important factors for the growth of European nanotechnology in thermoelectricity R&D during the next decade are higher support from the EU and national governments (52%) and higher interaction between EU academia and industry (32%). In contrast only 7% (three experts) thought that Europe needed to recruit highly skilled personnel from other regions.

Most important factors for the growth of European nanotechnology in thermoelectricity R&D



However, when considering the industrial applications of this research (i.e. nanotechnologies) the perspective is much gloomier, with the vast majority thinking that European industry (in particular large companies) were much poorer than other regions. This is further supported by the fact that most companies cited by experts as contributing the most to advancing nanotechnology in thermoelectricity are located in the US.



Region	Company (number of citations by experts)
Europe	Infineon (3), Micropelt (spinout from Infineon), CIDETE, Rittal.
N. America	Research Triangle Institute (4), Nextreme Thermal Solutions (spinout from RTI- 4), DuPont (3), General Motors (2), BSST, NASA, UBE, IBM, Evident Tech., Marlow Industries, Hi-Z, Melcor, NanoCoolers, II-VI Inc., Amerigon.
Asia	Toyota (2), Komatsu (2), Seiko, Tokyo Electric Power Co..

2.4 Conclusions

Nanoscience research in thermoelectricity is seen as relatively poor compared with other regions and so, not surprisingly, is European industry. The vast majority of companies cited by experts as contributing the most to advancing nanotechnology in thermoelectricity are based in the USA (sixteen out of twenty-four).

What can be the reasons? Many experts believe that developments and new findings are occurring earlier than expected. This implies that this sector of energy research is developing much faster than e.g. solar cells where ten years ago this could be the case, but not so five or two years ago. This in turn makes it more difficult to keep abreast of developments, compete with other groups and therefore exploit new applications. In addition, more thermoelectricity experts than in other energy categories stated that they had problems accessing infrastructure and that equipment costs were rising, both of which could hinder the rate of R&D.

Most experts agree that nanotechnology will play an important role in thermoelectricity applications by 2014 and this will most likely be due to decreasing thermal conductivity and increasing thermal power possibilities. To achieve these goals the main criteria at the moment is identifying and developing new materials, particularly those with high ZT values, increasing their stability, and of course reducing costs. This research would be expected to be applied in device fabrication by 2009, with first applications (in the case of energy generation from waste heat in vehicles) as early as 2014. The types of new materials are expected to be thin-films, nanocrystalline materials, nanoparticles, nanowires and also superlattices, with thin films and nanocrystalline materials expected to be first into applications. As can be seen, the list is long- there are a large number of compounds which could be developed in this area and also several potential applications. For example some materials will be better candidates for electricity generation, some for cooling purposes, and others will offer a dual role.

In contrast to solar energy, the acceptable relative costs of these new technologies are expected to be higher, presumably as the market is still in its infancy with few effective products, and because such new materials can have dual roles e.g. cooling components down in pc's while powering electric fans to further assist the cooling process.

The barriers that exist to the successful EU exploitation of nanotechnologies in thermoelectricity include:

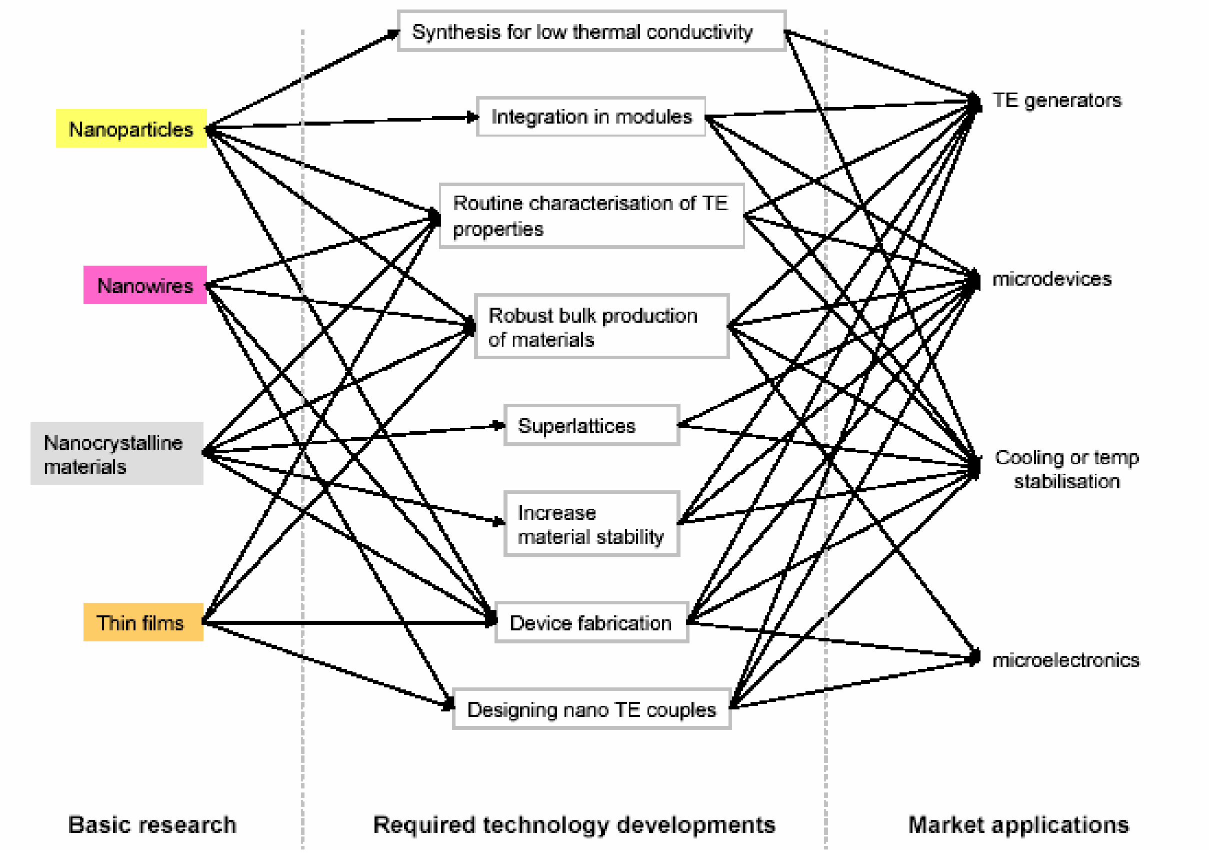
- global competition- other groups particularly in the USA have been and will continue to develop technologies and exploit them much faster
- most experts are manufacturing their own nanoparticles and materials for their R&D. Industrial partners will be needed to scale-up this manufacturing process to be cost-effective
- effectively researching quite a wide spectrum of materials, which may have quite a wide range of potential applications

Potential solutions to overcoming these barriers include:

- collaboration with groups outside the EU to gain knowledge and expertise
- greater numbers of smaller projects with stronger collaborations between partners that will allow a wide spectrum of topics to be investigated

The diagram on the following page summarises areas of research, their eventual applications and the technological developments which will be needed to achieve these.

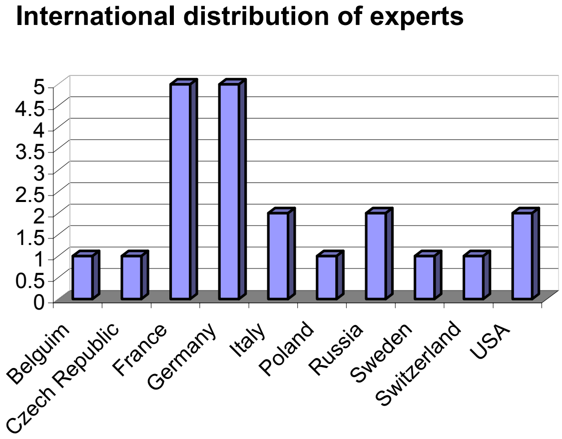
<u>Basic research underway with the technology developments required to achieve the desired applications</u>



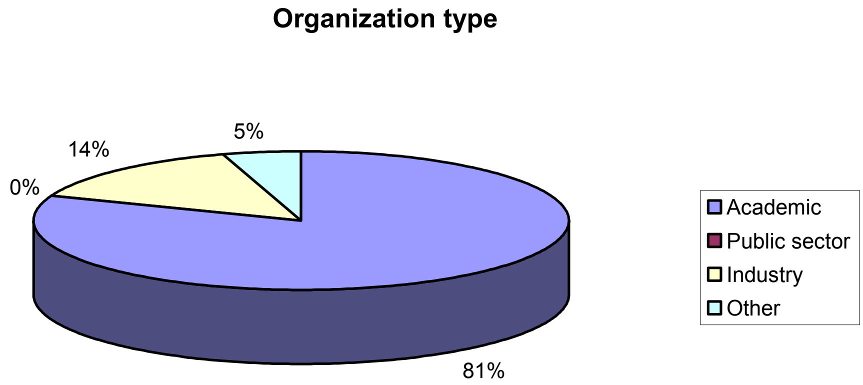
Appendix

Statistics

Over 25 experts were asked to take part in the questionnaire of which 21 completed and returned the questionnaire. The international distribution of experts is shown in the graph below.



The types of organization represented by those experts completing the questionnaire were Academic, Industry and Other (no public sector representatives responded). Academics represented the largest group of respondents (81%) as can be seen from the chart below. The expert who selected the "Other" category was from a Fraunhofer Institute in Germany which is non-governmental and non-profit.



List of Experts

Prof. Fernande Grandjean, University of Liege, Belgium	Dr. Jiri Hejtmanek, Senior Researcher, Institute of Physics, Academy of Sciences, Czech Republic	Prof. Clotilde Boulanger, University of Metz, France
Dr. Didier Ravot, Researcher, CNRS UMII, France	Dr. Anne Dauscher, UMR CNRS-INPL-UHP, France	Antoine Maignan, Director of CRISMAT, CNRS, France
Claude Godart, Director Research, CNRS, France	Frank Steglich, Director, Max Planck Society, MPI-CPfS, Germany	Dr. Jens Biele, DLR, Germany
Dieter Platzek, CEO PANCO, Germany	Fritz Volkert, MD Infineon Tech AG/Micropelt, Germany	Prof. Harald Boettner, Fraunhofer Inst. for Phys. Measurement Techniques, Germany
Dr. Sergio Ceresara, University of Florence, Italy	Dr. Carlo Gatti, CNR-ISTM, Italy	Prof. Krzysztof Wojciechowski, AGH University of Science and Technology, Poland
Alexander Ivanov, General Director, RIF Corp., Russia	Dr. Alexander Burkov, A.F.Ioffe Physico-Technical Institute, Russia	Prof. Mamoun Muhammed, KTH, Sweden
Anke Weidenkaff, Group Leader, EMPA, Switzerland	Prof. Heiner Linke, University of Oregon, USA	Prof. Ali Shakouri, University of California Santa Cruz, USA

NanoRoadMap is a project co-funded by the 6th Framework Programme of the EC

Draft RoadMap on Batteries and Supercapacitors

The Institute of Nanotechnology

October 2005

Partners

1. Introduction

1.1 Background

The NanoRoadMap (NRM) project, co-funded by the European Commission (EC), is aimed at road-mapping nanotechnology related applications in three different areas:

- Materials
- Health & Medical Systems
- Energy

Within the project, an international consortium consisting of eight partners covering eight European countries and Israel, has joined forces to cover the time-frame for technological development in this field up to 2014. The results of the NRM project are to be used by any European entity interested in planning an R&D strategy taking into account nanotechnology. An important potential user is of course the EC itself in the preparation of the 7th Framework Programme (FP7) for research and technology development. For additional information on the NRM project, please refer to www.nanoroadmap.it

1.2 Goals

The primary objective of NRM is to provide coherent scenarios and technology roadmaps that could help the European players to optimize the positive impact of nanotechnology on society, giving the necessary knowledge on its future development and when technologies and applications will come into full fruition.

The key users of the reports are mainly European SMEs, research organizations, public bodies in general and the EC in particular. Even though a special focus is put on SMEs, these roadmaps are also meant to be useful for larger corporations.

This report is one of the three final deliverables of the NRM project and it is aimed at providing a thorough overview of specific topics selected for road mapping within the field.

1.3 Methodology

1.3.1 Collection and synthesis of relevant existing information

In October 2004 three sectoral reports were published, each covering one of the above mentioned areas. They were based on the collection and synthesis of existing public sources in 31 countries and were published as key input for the celebration of the First NRM International Conference held in Rome the 4th – 5th of November 2004. The full report can be downloaded for free on the project web site.

The report within the energy sector focused on reviewing the different aspects of nanotechnology in 10 topics, giving its definition, describing its most remarkable properties, current and future markets and applications, and leading countries and highlighted R&D activities in the field. A general review of non technological aspects (social, legal, ethical and health and safety aspects, but also economical aspects and infrastructures requirements) was also performed.

The 10 topics identified, even not being completely homogenous in terms of scope or classification, were intended to adequately cover the field of energy. The following list was agreed upon the different partners of the NRM project (similar classifications can be found in the existing bibliography):

- Solar cells
- Fuel cells
- Thermoelectricity
- Rechargeable batteries
- Hydrogen storage
- Supercapacitors
- Insulation
- Glazing Technology for Insulation
- More efficient lighting
- Combustion

1.3.2 Selection of Topics

Another major goal of that report was to set the basis for discussion and selection for road mapping of 4 out of the 10 topics identified above. A preliminary selection of topics was presented during the First International Conference in November, 2004.

After a thorough discussion, which involved international experts in the field of nanotechnology, four topics were selected (and validated in dialogue with the European Commission). The subjects were partly combined with each other, leading to the four chosen topics:

- Solar cells
- Thermoelectricity
- Rechargeable Batteries and Supercapacitors
- Heat Insulation and Conduction

1.3.3 Roadmaps elaboration

One draft roadmap will be prepared for each of the four aforementioned topics. Their preparation and execution will be based upon a Delphi-like approach. The methodology consists of 2 cycles, which is the same for the four topics. The Delphi exercise consists in:

- Selecting top-international experts on the field
- Preparing a dedicated questionnaire for each of the topic to be road mapped
- Circulating the questionnaires and gathering experts' responses (1st cycle)
- Preparing a first summary of the given answers
- Circulating the summary and partly interpreted data, asking for feedback (2nd cycle)
- Elaborating the roadmap

Through one international and eight national conferences these reports will be proposed to the interested partners and comments collected so as to build up final definitive roadmap.

2. Road Map on Rechargeable Batteries and Supercapacitors

2.1 Definition of Rechargeable Batteries and Supercapacitors

Rechargeable batteries and supercapacitors provide portable power supplies that can be replenished by connection to an electrical supply. As such they can offer complete renewable energy solutions when combined with solar cells or wind generators, storing surplus energy when being supplied by natural forces and providing energy at night or when there is no wind.

Rechargeable batteries

These store electrical energy in a chemical form, which can later be released. The lead-acid battery in cars represents one of the earliest examples, however the largest market at present concerns the smaller, portable batteries used in the plethora of modern-day electronic devices. There has been a steady progression of materials from the original compact rechargeable Nickel-Cadmium (NiCd) batteries to Nickel-Metal-Hydride (NiMH) and then Lithium-Ion (Li-ion) and Lithium-polymer. This progression has demonstrated improved power outputs and faster charge/discharge cycles, but it is still limiting for many power-hungry, modern devices. Lithium is the most electropositive and also the lightest metal, making it the element of choice for rechargeable batteries. In all cases Lithium is incorporated into a support scaffold of another metal oxide which makes up the anode. During charging it migrates to the cathode (generally graphite) and is then released again to migrate back to the anode when the battery is put under a load.

Most R&D is now focused on how to deliver Li in the rechargeable battery to maximize power output, charge/discharge time, and number of charge/discharge cycles.

Supercapacitors

Capacitors store electrical energy (rather than chemical energy in batteries) and so can deliver much more power than a battery. However they suffer from low energy density, and so they can deliver short powerful bursts of energy and are then depleted. Supercapacitors offer a solution to this, by combining the advantages of capacitors with the larger energy storage of batteries, and as such have a promising future for more power-hungry applications. The main determining factor for power density and maximum power output is the surface are of each electrode that makes up the capacitor. Supercapacitors utilize nanostructured materials which dramatically increase this surface area (e.g. up to 1000m^2 per gramme of carbon).

There are several different electrode platforms that are being explored for both batteries and supercapacitors and these are described below:

Carbon nanotubes

The large surface area and porosity of carbon nanotubes means that they can accommodate much more lithium than normal graphite rods. In addition the diffusion time of lithium between electrodes is reduced, consequently such such electrodes offer an increase in power and faster charge/discharge rates. For supercapacitors the increased surface area leads to a concomitant increase in capacitance.

Aerogels

These are highly porous matrices of usually carbon particles, but can also be silica, which can be up to 99.8% air, have a large surface area and can accommodate other materials.

Nanocomposites

Nanocomposites contain two or more different nanomaterials which provide different functions e.g. electrical and structural support, as well as offering higher surface area.

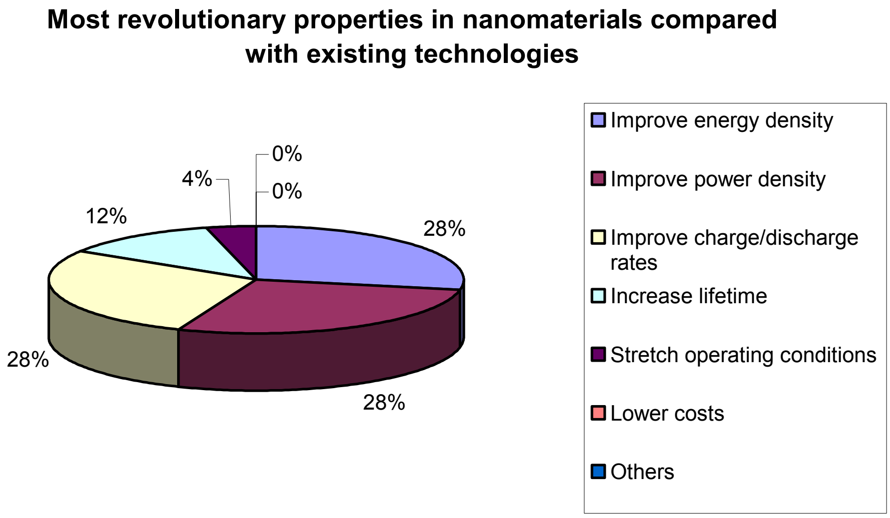
Different materials and combinations of materials are being developed for Li-ion batteries to offer more robust platforms.

Nanocrystalline materials

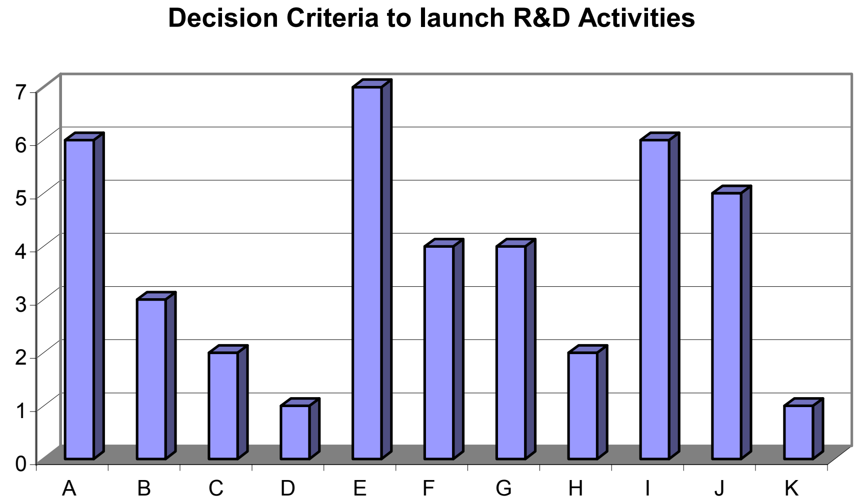
These can have precisely defined structures including pore-size as well as high surface area, both of which are critical for supercapacitor electrodes.

2.2 Scientific and Technological Aspects

Portable devices such as mobile phones, PDAs and laptops continually offer more functionality with an associated higher energy tag. Current portable power supplies (mainly rechargeable batteries) are struggling to meet this demand as they still suffer from limited energy reserves, maximum power output and slow charge/discharge rates. Current technologies are limited not so much by the materials but by the active surface area, e.g. it is estimated that only 25% of the volume of a rechargeable batteries is actively used. So it is of little surprise that the most revolutionary properties of nanoparticles in rechargeable battery and supercapacitor R&D compared to existing/alternative technologies are seen as their ability to improve energy density, power density, and charge/discharge rates (see below).

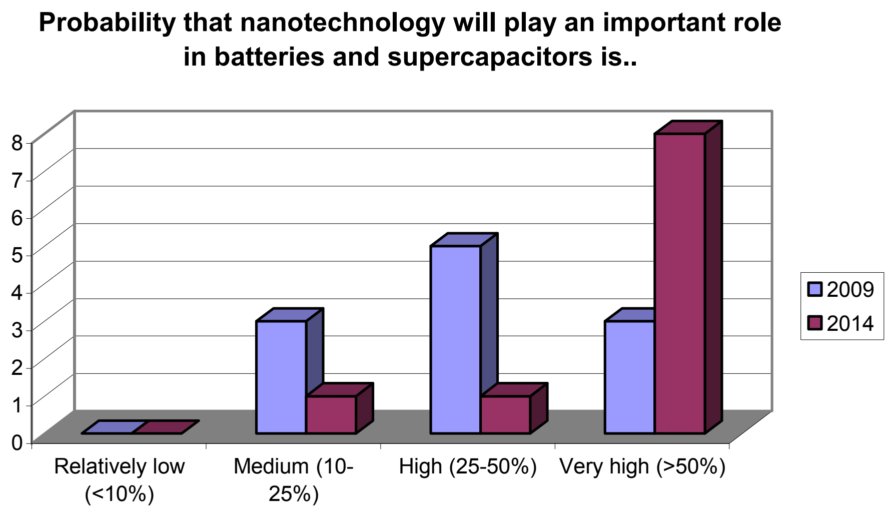


One of the main driving factors for launching new R&D activities is specific market entry followed by low costs of estimated product and scientific reputation.



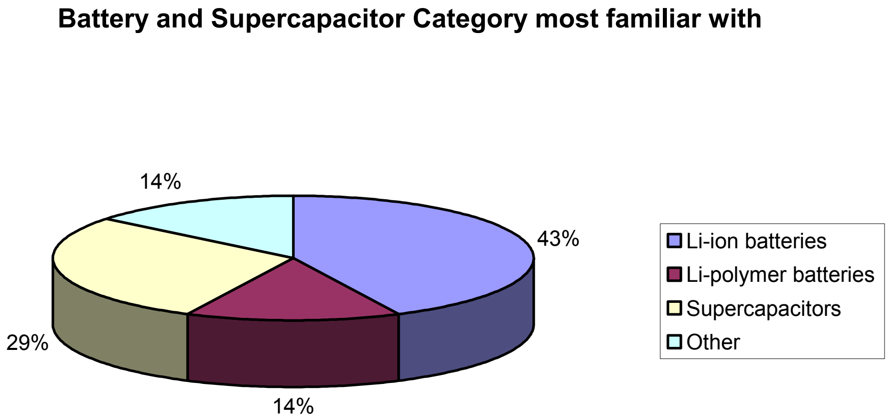
A. Low costs of the estimated product
B. Low costs of research process
C. Short time to market
D. Rapid readiness for start of production/product maturity
E. Specific market entry
F. Broad market entry
G. Possibility of governmental subsidy
H. Possible patent announcements
I. Scientific reputation
J. Possible publications in scientific journals of high reputation
K. Other

All experts were of the opinion that there was at least a medium probability that nanotechnology will play an important role in rechargeable battery and supercapacitor manufacture by 2009 (eight out of ten thought that there would be a high or very high probability of this), with nine out of ten expecting nanotechnology to play an important role by 2014.



2.2.1 Basic Science

The experts contacted for this Delphi questionnaire, have a wide background in rechargeable battery and supercapacitor R&D, with most interest in developing improvements to Li-ion and Li-polymer batteries. One expert was involved in R&D in all three categories plus rechargeable magnesium batteries, another in both Li-polymer batteries and supercapacitors, and two others worked with fuel cells.

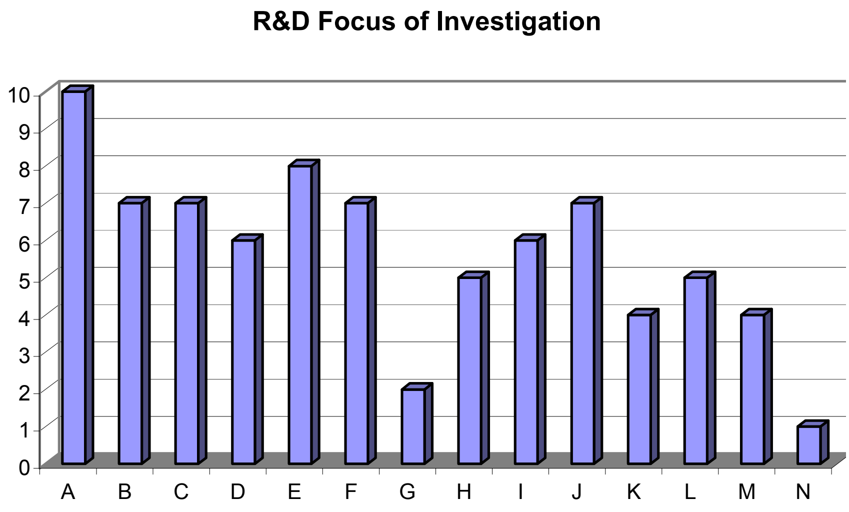


Most of the experts are engaged in several different but interrelated R&D activities, with ten out of eleven developing new high energy electrode materials and more stable electrolytes to maximize power and energy output from batteries. As befits the early stage integration of established active materials with new platforms and technologies, there is relatively less effort devoted to the decrease of manufacturing costs at present. However, within the next ten years the major nanotechnological challenges in rechargeable battery and supercapacitor development will include:

- scaling up from laboratory processes.
- ensuring stability and safety of materials.
- ensuring material performance.
- lowering costs.

And more specifically:

- integrating nanoparticles in support materials.

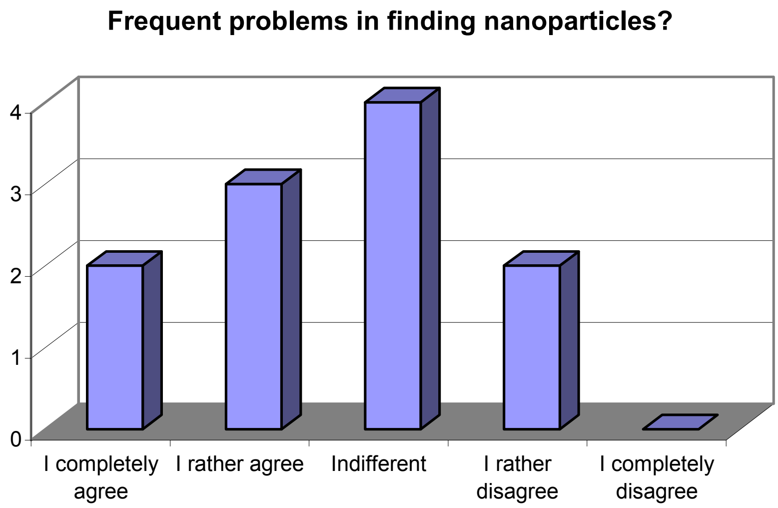


A. Increasing the energy content of current batteries by high-energy electrode materials and more stable electrolytes
B. Increasing the lifetime of electrochemical power systems
C. Increasing energy storage efficiency
D. Decreasing the size and complexity of the energy storage system
E. Developing lightweight energy storage with high current density i.e. increasing specific volume energy
F. Tailoring electrode materials and electrolytes
G. Decreasing lithium dendrite formation
H. Improving conductivity
I. Improving charge/discharge rates
J. Improving electrochemical stability, power
K. Enhancing the electrochemical reactivity
L. Improving dynamics i.e. charge and discharge rates
M. Reducing production costs
N. Others

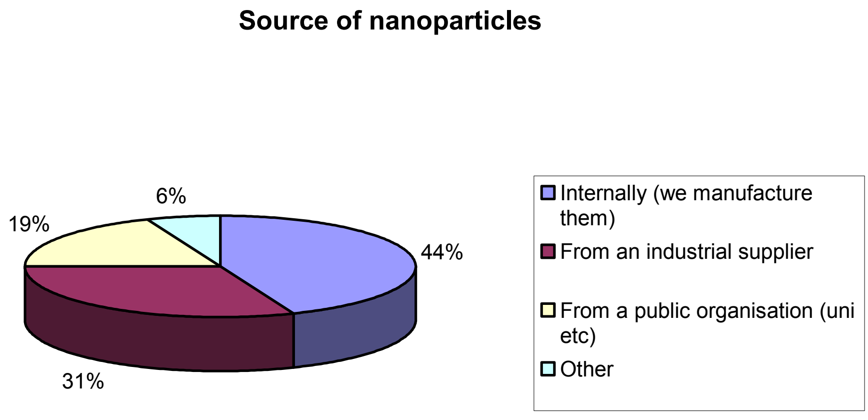
2.2.2 Nanotechnologies in rechargeable batteries and supercapacitors – Value Chain

Production

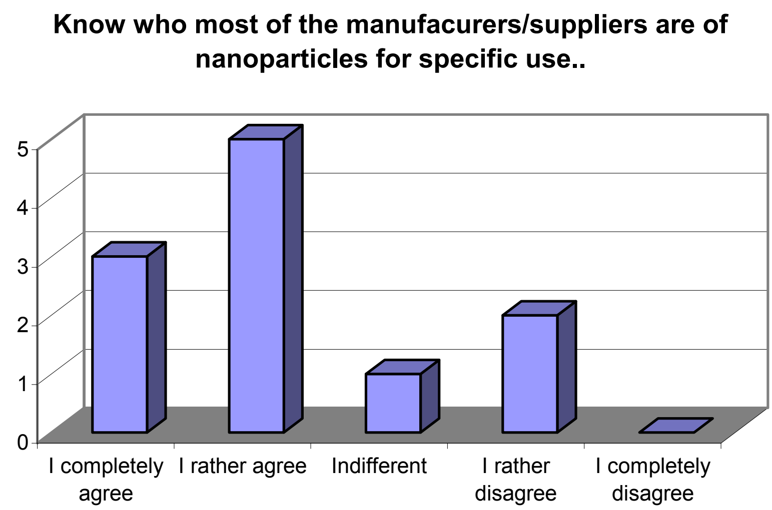
Five experts completely or rather agreed that they have frequent problems in finding nanoparticles to satisfy their R&D and/or manufacturing needs in rechargeable batteries and supercapacitors with two disagreeing. The remaining four were indifferent about this matter.



Several experts use nanoparticles from two sources (internally manufactured and from an industrial supplier), however one expert did not use nanoparticles in R&D activities and one was developing materials in collaboration with an industrial partner (see chart below).

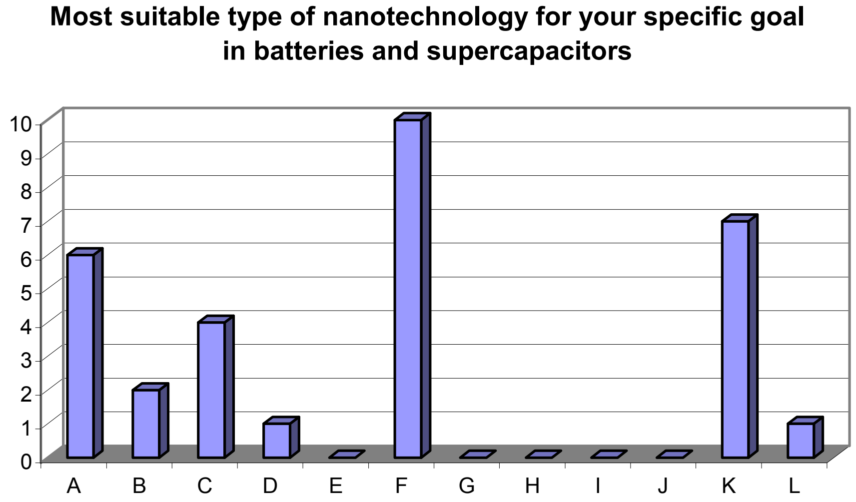


There was no strong correlation between difficulty in finding nanoparticles and source, with some experts using internally produced materials for their R&D still experiencing difficulties in supply. Interestingly, those experts who had no internal source were more likely to have frequent supply problems, even if they were of the opinion that they knew the majority of industrial suppliers.



Functionalisation

Nanoparticles are the most extensively used materials for R&D applications by the experts participating in this survey (ten out of eleven experts) followed by nanocrystalline materials and thin films. When asked what they deemed to be the winning category of nanotechnology for rechargeable batteries and supercapacitors, nanocomposites and nanoparticles were the top choices, with thin films, carbon nanotubes and nanowires also mentioned by individual experts.



A. Thin films, layers and surfaces
B. Carbon nanotubes
C. Inorganic nanotubes
D. Nanowires
E. Biopolymers
F. Nanoparticles
G. Fullerenes
H. Dendrimers
I. Quantum wells
J. Quantum dots
K. Nanocrystalline materials
L. Others

2.2.3 Application

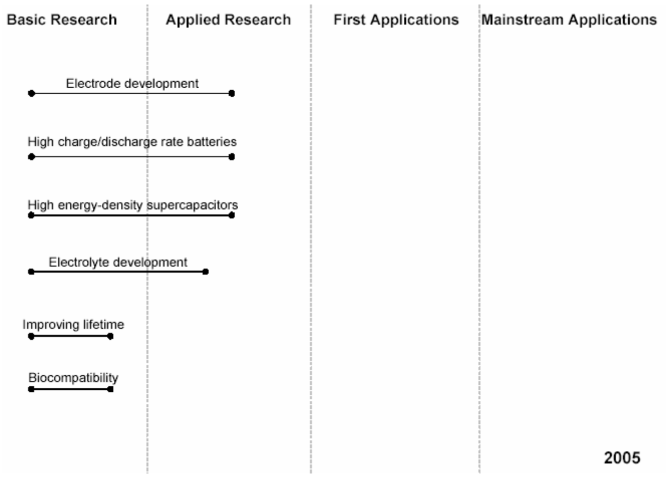
Expanding on this, experts were asked to identify the most important R&D topics to them and chart their progression over the next nine years, from basic R&D through to current applications. The definitions used for each stage in the development process are given below, and the charts describing this progression are on the following page:

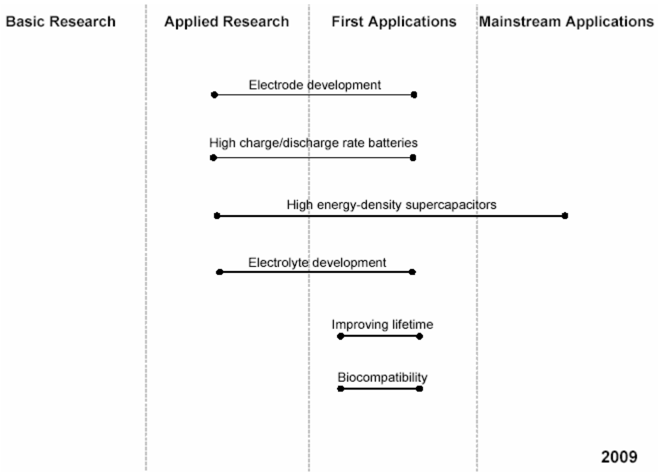
Basic R&D phase: applications in this phase have received the interest of one or more researchers in the world. Some applications might still be in early development, while others are tough to develop and need a lot of basic research to be understood. The object of basic R&D is to validate the original hypothesis. Various applications are currently in this phase.

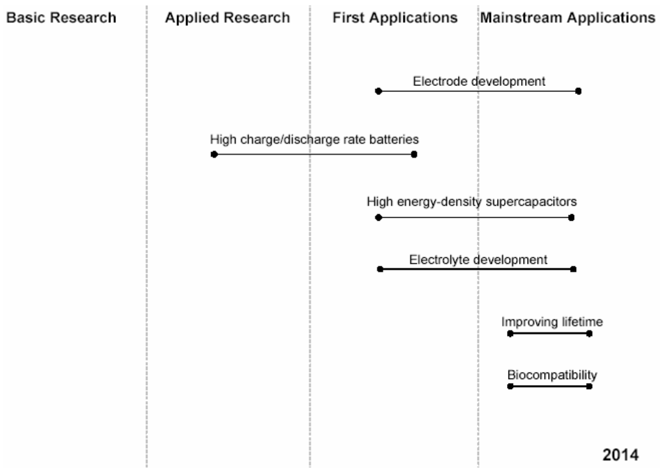
Applied R&D phase: after the hypothesis is validated, research typically (but not necessarily) moves from pure research labs to more commercial labs and companies. Applied R&D will eventually result in a proof of concept, a successful demonstration model. While the production issues might not have been solved yet, a successful prototype/model has been validated.

Product R&D phase (**first applications**): after demonstrator models and prototypes, initial, usually prohibitively expensive, small numbers of products may be produced. If these prove successful, companies will seek to enhanceproduction to gain market share. Generally at some point, demand increases sufficiently to offset the investment needed to start production. This phase ends at a point when feasibility proven and production is to start.

Production level and incremental research (**mainstream applications**): the final development phase, when production has reached significant numbers and research focuses on incrementally improving the products.



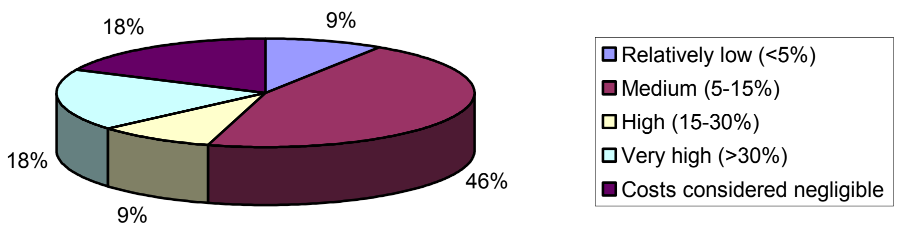




The development of new electrode materials is seen as one of the most important topics for R&D. For battery electrodes different materials for cathodes and anodes need to be developed plus their interaction with lithium ions studied in full over many charge/ discharge cycles to ensure long-term stability. For supercapacitors, the issue is manufacturing electrodes with different sized nanoscale pores to better accommodate the electrolyte anions and cations, and enhance power and energy density. For both types of energy supply both carbon nanotubes and porous nanocrystalline materials are receiving a lot of attention. The development of new electrolytes will also be important over the next decade and this includes nanocomposites combined with conductive polymers for use in Li-ion batteries.

Given the demand for portable power supplies, experts predict that the rechargeable battery and supercapacitor market will accept medium to high cost increases as a result of nanotechnology advances. In fact two experts are of the opinion that as no conventional approach exists, the costs would be considered negligible when compared with the tremendous benefits associated. Only one expert thinks that no more than a relatively low cost increase would be accepted.

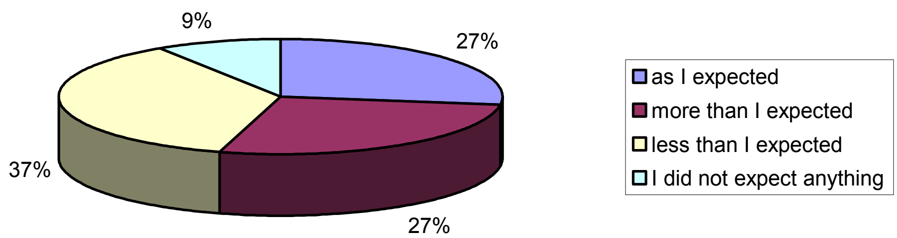
Maximum cost increase accepted by the market



2.2.4 Retrospect

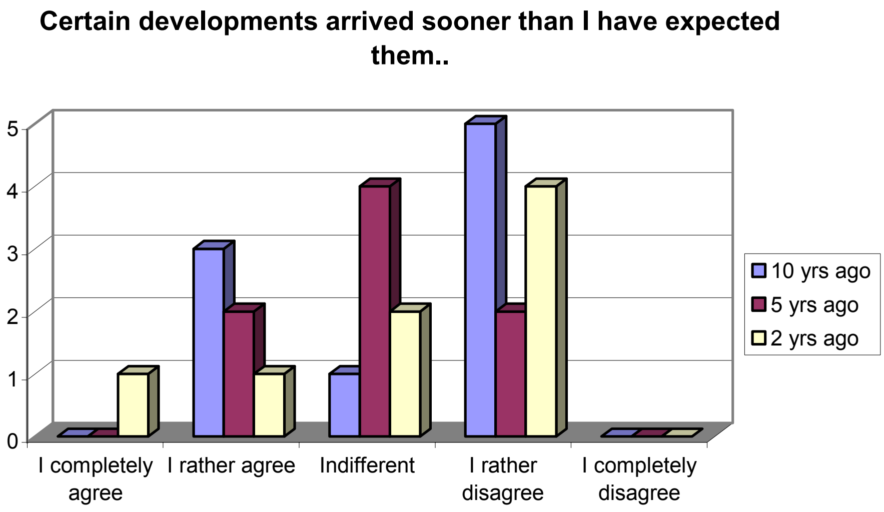
Rechargeable battery and capacitor technology is well established, however the impact of nanotechnology has been more recent; so it was important to gauge how experts perceived this progress. In fact there was no consensus of opinion on the current nanotechnological progress of rechargeable batteries and supercapacitors (see below).

Current nanotechnological progress is advanced..

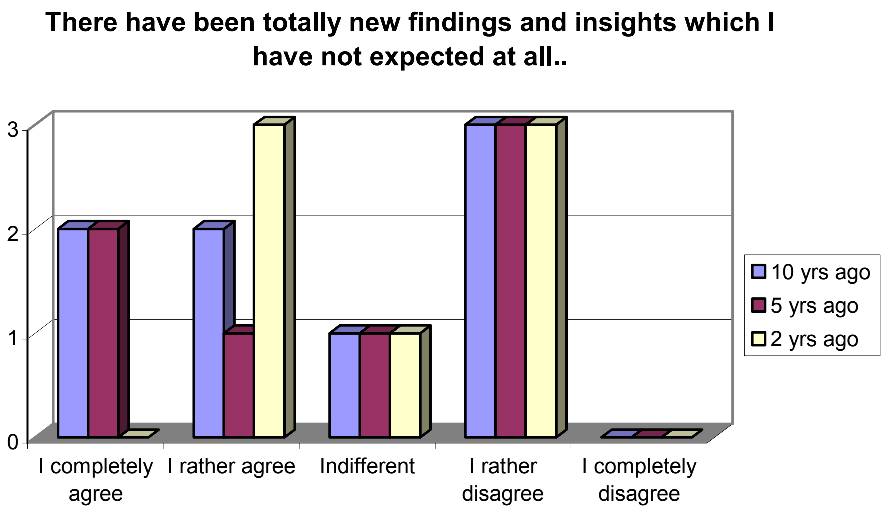


There was also no consensus amongst experts on the question of developments arriving sooner than expected over the past ten years, although more experts disagreed that developments had appeared sooner than expected- particularly ten years ago (see below). However specific examples cited included: improvements to the lifespan, safety and efficiency of materials; nano-structured composite electrolytes.

Other experts thought that on the contrary certain developments had not taken place as early as they expected such as the adoption of nanomaterials into electrodes.



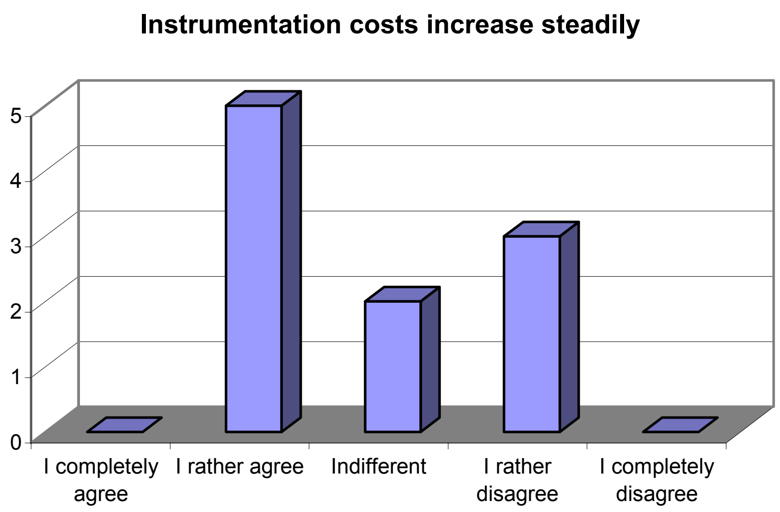
Neither was there consensus to the statement “there have been totally new findings and insights which I have not expected at all.” (see below). However specific examples of totally new findings and insights included: enhanced surface capacitance of nanocrystalline materials; ionic liquids; nanoalloy anodes; MnNi cathodes; crystalline polymer electrolytes.



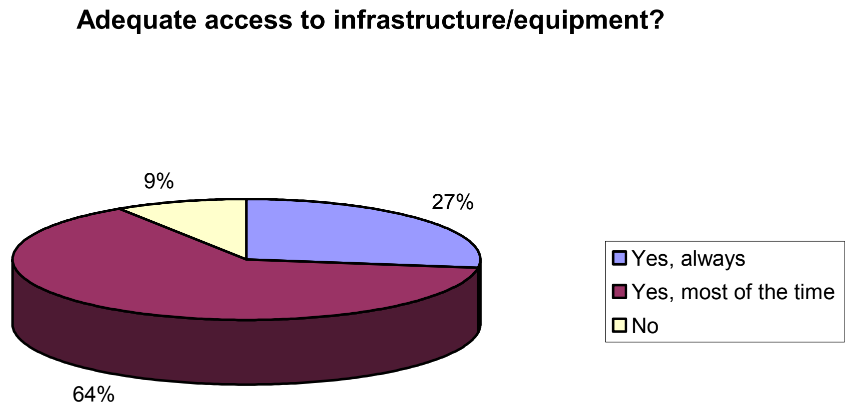
2.3 Non Technological Aspects

2.3.1 Infrastructure Requirements

Experts were asked whether the instrumentation costs for the manufacturing, characterization and manipulation of nanotechnologies in the application(s) areas of rechargeable batteries and supercapacitors have increased steadily. Five respondents thought that costs had increased compared with three who did not. Two were indifferent.



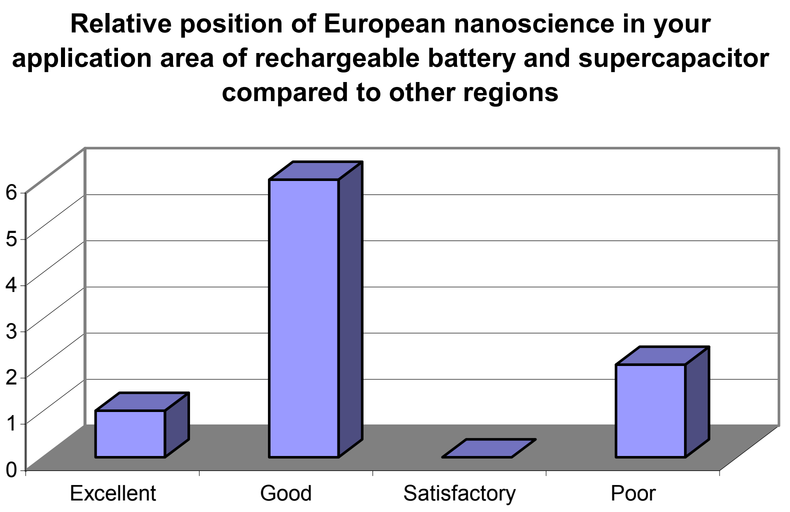
Access to infrastructure/equipment for the performance of typical nanotechnology-related activities (which includes the use of both own and external facilities through existing collaboration) is not perceived to be problematic for most experts. All but one expert answered that they had access most or all of the time.



2.3.2 Economic Aspects

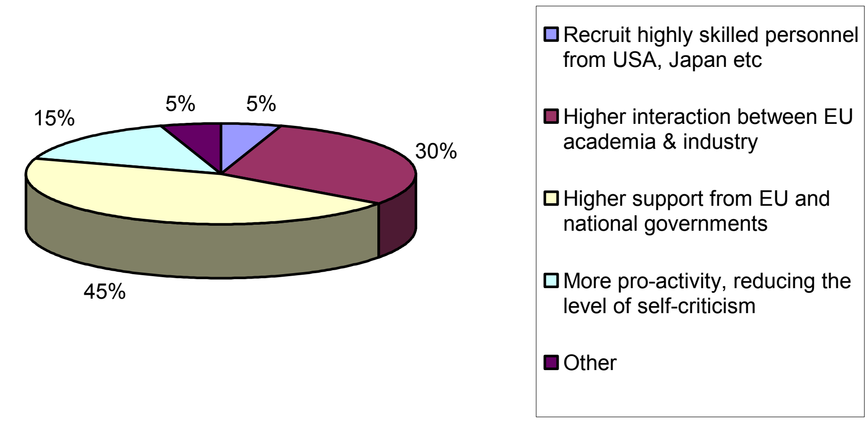
The rechargeable battery market is growing year on year. The turnover for all batteries in Europe was almost €3 billion in 1999; a value of more than €4.6 billion is expected for 2006.[1]

European nanoscience research in the field of rechargeable batteries and supercapacitors is seen to compare very well with other global regions, with only two experts thinking that Europe is relatively poor. Experts were asked how the European Commission could contribute most to advancing state-of-the-art nanotechnology in their application areas. Seven experts said this could be achieved by supporting more, smaller collaborative R&D projects rather than fewer, bigger collaborative R&D projects (two experts). The experts favouring smaller projects do so as they believe that this would allow a greater interaction between researchers, competition, and nurture lateral thinking and imaginative R&D. One expert felt that both types of project were needed and another that large projects would ensure that more academic groups would receive a fairer share of the funding than industry.



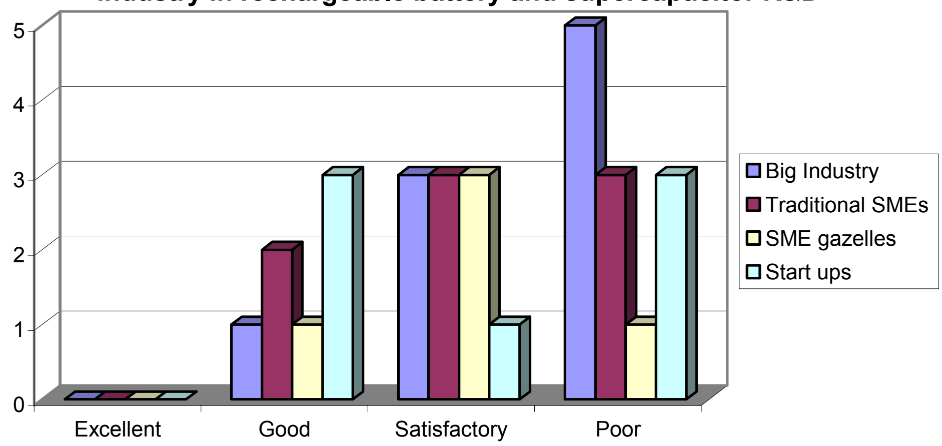
To ensure that European nanotechnology continues to grow in this area, the two most important factors during the next decade will be higher support from the EU and national governments (nine experts) and higher interaction between EU academia and industry (six). In contrast only one expert thought that Europe needed to recruit highly skilled personnel from other regions (see graph below). One expert believed that funding should be targeted towards autonomous support for the top research groups.

Most important factors for the growth of European nanotechnology in rechargeable battery and supercapacitor R&D



In contrast to the buoyant opinion of EU nanoscience, industry does not fare as well with no expert believing that the European nanotechnology industry is excellent, however more believe that it is satisfactory or good than not, with the exception of big industry which is seen as poor by five respondents (see below). This is a more positive view than for other energy sectors such as thermoelectricity, which is generally regarded as comparing poorly with the US in particular.

Relative worldwide postion of European nanotechnology industry in rechargeable battery and supercapacitor R&D



When asked to identify the top three to five industrial players worldwide who are contributing the most to advancing nanotechnology in solar cells, almost as many European companies were cited by experts as those located in the USA or Japan.

Region	**Company (number of citations by experts)**
Europe	SAFT, UMICORE, Süd Chemie
N. America	3M, PolyPlus
Asia	Sony (3), Toshiba, Sanyo, Samsung

2.4 Conclusions

European nanoscience in the area of rechargeable batteries and supercapacitors is seen as comparing well to other regions. Opinions on European industry are not as clear-cut; so as with other energy sectors, Europe is not seen to be exploiting nanotechnologies as efficiently as other global regions.

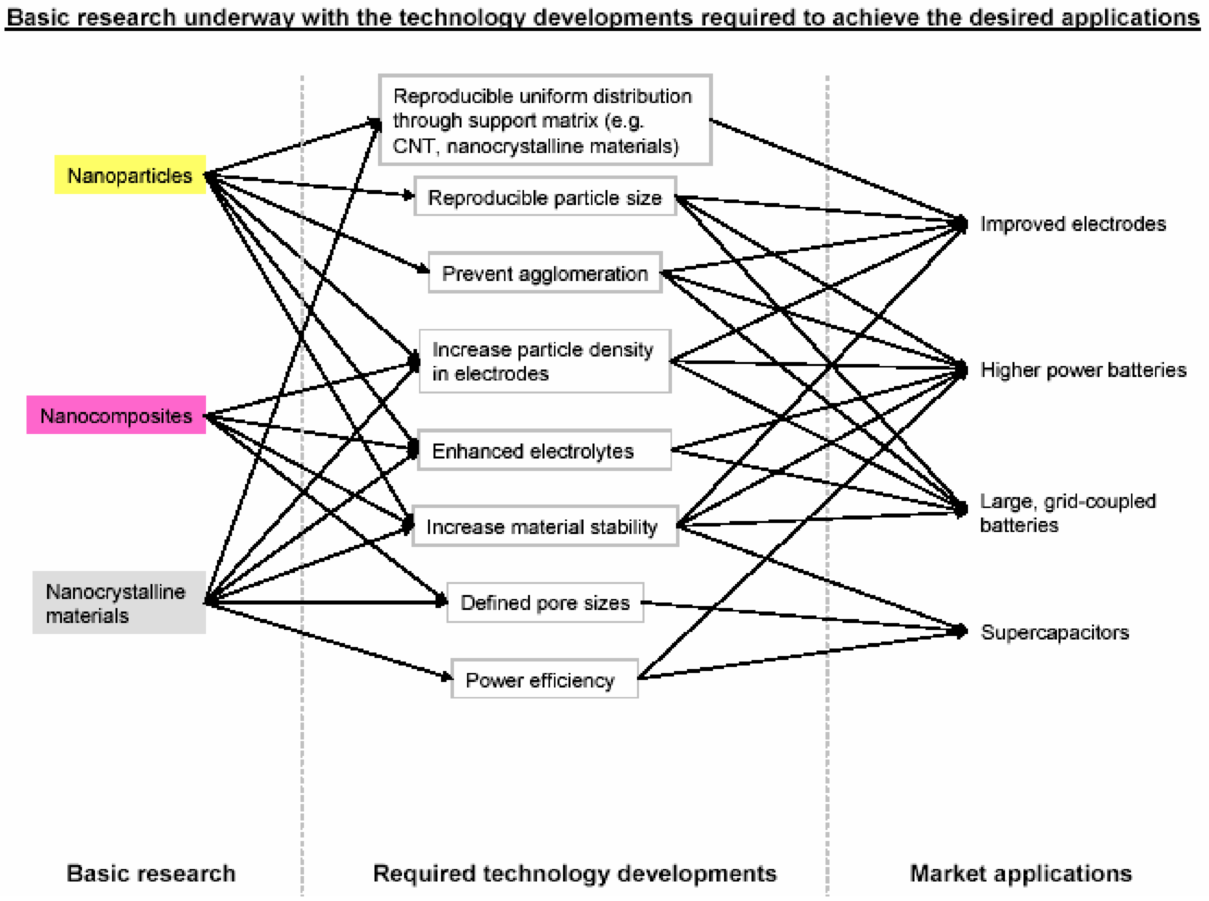
Nanotechnology is expected to play an important role in rechargeable batteries and supercapacitors as early as 2009, with this position strengthened by 2014. A relatively high increase in cost is expected to be tolerated by the markets due to the improvements in performance offered by nanotechnologies. The impact will be in several areas including improved energy density, improved power density, and improved charge/discharge rates. To achieve this, the main R&D focus is expected to be on electrode development with some on electrolytes. The applications that will arise from this are higher charge/discharge rate batteries and high energy supercapacitors.

The key issues at stake in achieving these goals are scaling up from laboratory processes and ensuring the stability and safety of materials.

Analyzing the answers of the limited pool of experts it can be seen that, relative to the solar cell and thermoelectricity sectors, more experts source nanoparticles for their research from industrial sources, however they often have difficulty with this. As most suppliers are known to the experts, and nanoparticles are used by all but one of the experts, then this could have severe limitations on R&D. One expert was addressing this by developing nanoparticles in collaboration with an industrial partner.

Equipment costs may play a role in achieving R&D goals, with slightly more experts believing that costs were increasing. On the other hand there does not appear to be any problems accessing infrastructure.

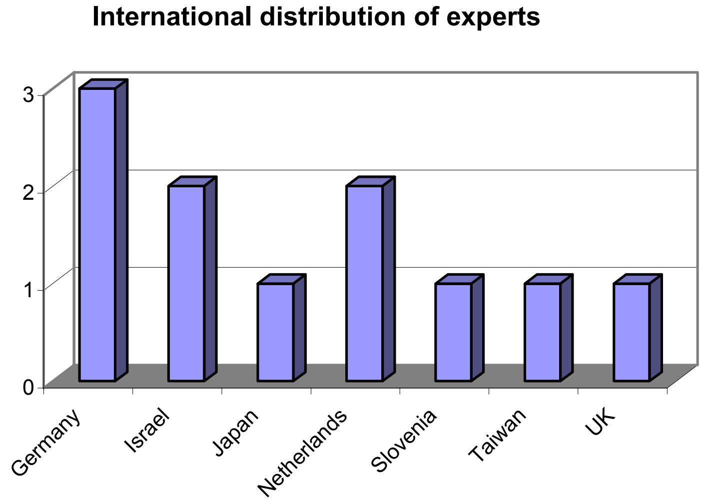
The development of basic science to applications is summarized in the diagram on the next page.


Basic research underway with the technology developments required to achieve the desired applications
Nanoparticles
Nanocomposites
Nanocrystalline materials
Reproducible uniform distribution through support matrix (e.g. CNT, nanocrystalline materials)
Reproducible particle size
Prevent agglomeration
Increase particle density in electrodes
Enhanced electrolytes
Increase material stability
Defined pore sizes
Power efficiency
Improved electrodes
Higher power batteries
Large, grid-coupled batteries
Supercapacitors
Basic research
Required technology developments
Market applications

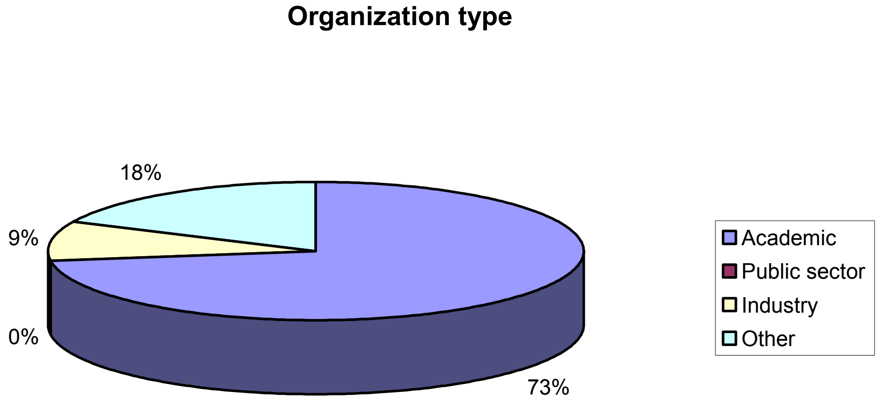
Appendix

Statistics

Within the topic of rechargeable batteries and supercapacitors over 25 experts were asked to take part in the questionnaire of which 11 completed and returned the questionnaire. The international distribution of experts is shown in the graph below.



The types of organization represented by those experts completing the questionnaire were Academic, Industry and Other. Academics represented the largest group of recipients (eight), with one from industry and two from private non-profit research organizations.



List of Experts

Dr. Uwe König, Head of NanoEnergie, Zentrum für Brennsoffzellentechnik GmbH, Germany	Mirko Lehmann, Manager, Micronas GmbH, Germany	Karl-Heinz Haas, Deputy Director, Fraunhofer-Institut für Silicatforschung, Germany
Dr. Avi Ulus, Tel-Aviv University, Israel	Prof. Doron Aurbach, Bar Ilan University, Israel	Prof. Hidehiro Kamiya, Tokyo University of Agriculture and Technology, Japan
Lambertus Plomp, Project Manager, Energy Research Centre, The Netherlands	Prof. Joop Schoonman, TU Delft, The Netherlands	Janko Jamnik Head of Laboratory, National Institute of Chemistry, Slovenia
Prof. Nae-Lih Wu, National Taiwan University, Taiwan	Prof. Peter Bruce, University of St Andrews, UK	

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[1] Gans: Spektrum der Wissenschaft, April 2002, 90-91

NanoRoadMap is a project co-funded by the 6th Framework Programme of the EC

Draft RoadMap on Heat Insulation/Conductance

The Institute of Nanotechnology

October 2005

Partners

1. Introduction

1.1 Background

The NanoRoadMap (NRM) project, co-funded by the European Commission (EC), is aimed at road-mapping nanotechnology related applications in three different areas:

- Materials
- Health & Medical Systems
- Energy

Within the project, an international consortium consisting of eight partners covering eight European countries and Israel, has joined forces to cover the time-frame for technological development in this field up to 2014. The results of the NRM project are to be used by any European entity interested in planning an R&D strategy taking into account nanotechnology. An important potential user is of course the EC itself in the preparation of the 7th Framework Programme (FP7) for research and technology development. For additional information on the NRM project, please refer to www.nanoroadmap.it

1.2 Goals

The primary objective of NRM is to provide coherent scenarios and technology roadmaps that could help the European players to optimize the positive impact of nanotechnology on society, giving the necessary knowledge on its future development and when technologies and applications will come into full fruition.

The key users of the reports are mainly European SMEs, research organizations, public bodies in general and the EC in particular. Even though a special focus is put on SMEs, these roadmaps are also meant to be useful for larger corporations.

This report is one of the three final deliverables of the NRM project and it is aimed at providing a thorough overview of specific topics selected for road mapping within the field.

1.3 Methodology

1.3.1 Collection and synthesis of relevant existing information

In October 2004 three sectoral reports were published, each covering one of the above mentioned areas. They were based on the collection and synthesis of existing public sources in 31 countries and were published as key input for the celebration of the First NRM International Conference held in Rome the 4th – 5th of November 2004. The full report can be downloaded for free on the project web site.

The report within the energy sector focused on reviewing the different aspects of nanotechnology in 10 topics, giving its definition, describing its most remarkable properties, current and future markets and applications, and leading countries and highlighted R&D activities in the field. A general review of non technological aspects (social, legal, ethical and health and safety aspects, but also economical aspects and infrastructures requirements) was also performed.

The 10 topics identified, even not being completely homogenous in terms of scope or classification, were intended to adequately cover the field of energy. The following list was agreed upon the different partners of the NRM project (similar classifications can be found in the existing bibliography):

- Solar cells
- Fuel cells
- Thermoelectricity
- Rechargeable batteries
- Hydrogen storage
- Supercapacitors
- Insulation
- Glazing Technology for Insulation
- More efficient lighting
- Combustion

1.3.2 Selection of Topics

Another major goal of that report was to set the basis for discussion and selection for road mapping of 4 out of the 10 topics identified above. A preliminary selection of topics was presented during the First International Conference in November, 2004.

After a thorough discussion, which involved international experts in the field of nanotechnology, four topics were selected (and validated in dialogue with the European Commission). The subjects were partly combined with each other, leading to the four chosen topics:

- Solar cells
- Thermoelectricity
- Rechargeable Batteries and Supercapacitors
- Heat Insulation and Conduction

1.3.3 Roadmaps elaboration

One draft roadmap will be prepared for each of the four aforementioned topics. Their preparation and execution will be based upon a Delphi-like approach. The methodology consists of 2 cycles, which is the same for the four topics. The Delphi exercise consists in:

- Selecting top-international experts on the field
- Preparing a dedicated questionnaire for each of the topic to be road mapped
- Circulating the questionnaires and gathering experts' responses (1st cycle)
- Preparing a first summary of the given answers
- Circulating the summary and partly interpreted data, asking for feedback (2nd cycle)
- Elaborating the roadmap

Through one international and eight national conferences these reports will be proposed to the interested partners and comments collected so as to build up final definitive roadmap.

2. Road Map on Heat Insulation and Conductance

2.1 Definition of heat insulation and conductance

Insulating materials are used to keep the temperature constant in an enclosed space such as a house or a vessel, either warmer or colder than the surroundings, and in doing so can protect the environment through the reduction of CO_2, NO_x and other greenhouse gases. Substantial quantities of energy are wasted daily in both homes and industry because of poor insulation. Advances in insulation will help reduce both energy demand and cost.

The basic requirement for thermal insulation is to provide a significant resistance path to the flow of heat through the insulation material. To accomplish this, the insulation material must reduce the rate of heat transfer by conduction, convection, radiation, or any combination of these mechanisms. Insulating materials can be adapted to any size, shape or surface.

There are two principal methods of achieving this: using a porous material which traps air or another gas (e.g. fibre glass, or rockwool), or applying a coating to reflect heat (such coatings can be used on glazing, and can be transparent to visible light).

The different materials being developed for insulation and conductance properties are described below:

Aerogels

Aerogels are highly porous matrices of usually carbon, but can also be silica, which can be up to 99.8% air and have pores and particles that are smaller than the wavelength of light. Discovered in the 1930s, they were initially thought to have no practical use. They have low conductivity, low solid density, high porosity high surface area and a high dielectric constant making them one of the best insulating materials available.

Thin films

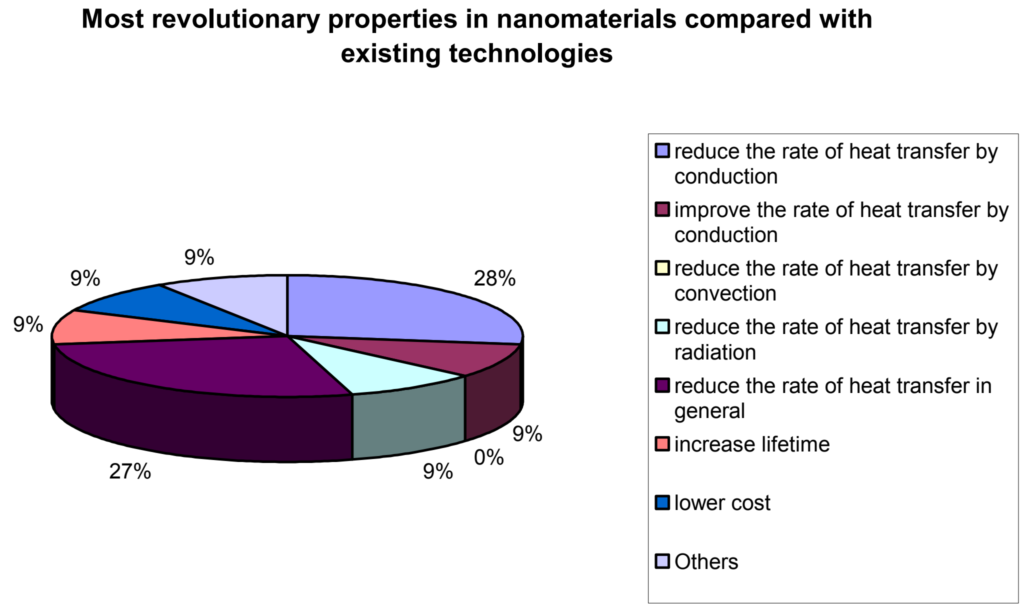
Photochromic, thermochromic and electrochromic thin films are being developed, primarily for glazing allowing windows to reflect heat while remaining transparent, or darken in response to increased UV light (these can be controlled electronically by the user).

Nanocomposites

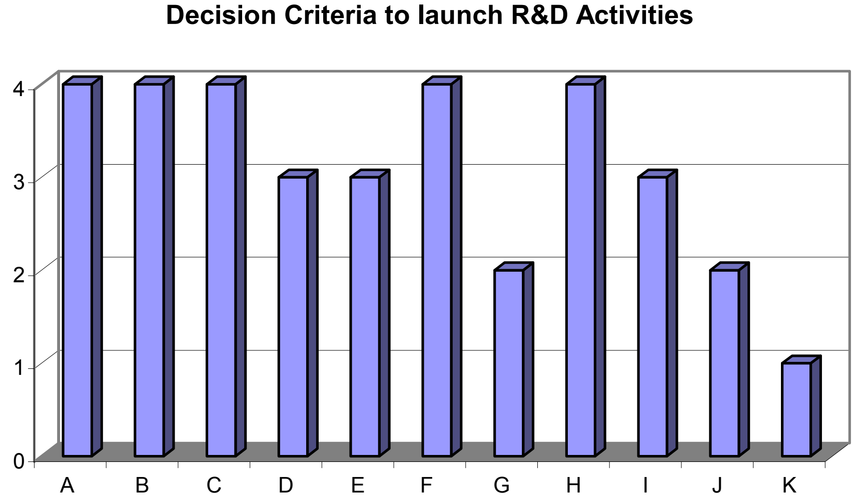
Materials containing nanoparticles are being developed for both insulating and conductance properties (e.g. helping to cool materials more quickly by boosting the rate of heat flow from them).

2.2 Scientific and Technological Aspects

Traditional insulating technologies can be bulky and/or heavy, and therefore even if they offer relatively high insulating efficiency can be inadequate for specific tasks. In terms of coatings for glazing, there is no effective traditional technology that provides effective insulation while remaining transparent. Nanotechnology on the other hand does offer solutions to these issues and according to the experts who participated in the Delphi questionnaire it does so primarily through reducing the rate of heat transfer (by various mechanisms). Only one expert thought that lower cost and another that increased lifetime are revolutionary. The "other" property described was tailored absorption and improved durability (see below).



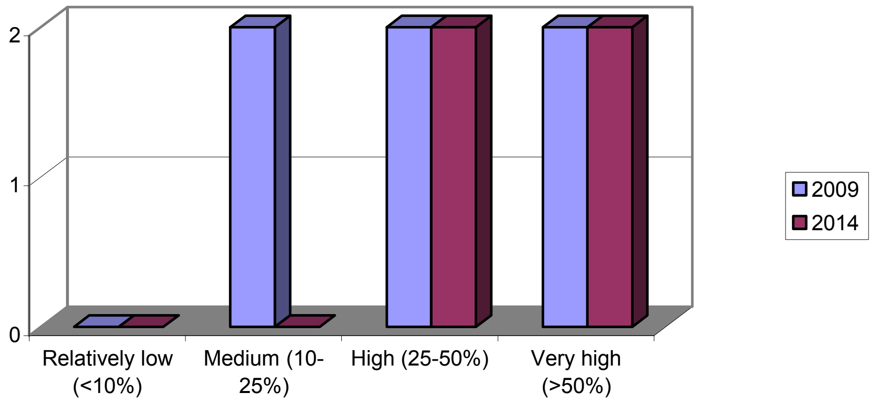
Several decision criteria are seen as important for launching R&D activities including costs and potential markets. In contrast to other areas of energy R&D, scientific publications were relatively less important, presumably reflecting the fact that the R&D in this area is more applied. The "other" criterion is the environmental and societal need, and latent demand for the R&D.



A. Low costs of the estimated product
B. Low costs of research process
C. Short time to market
D. Rapid readiness for start of production/product maturity
E. Specific market entry
F. Broad market entry
G. Possibility of governmental subsidy
H. Possible patent announcements
I. Scientific reputation
J. Possible publications in scientific journals of high reputation
K. Other

Reflecting this fact, nanotechnology is expected to play an important role in heat insulation and conductance applications as early as 2009.

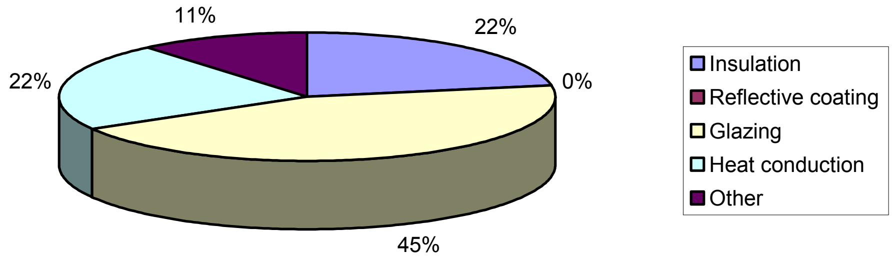
Probability that nanotechnology will play an important role in insulation and conduction is..



2.2.1 Basic Science

The experts contacted for the Delphi questionnaire work in a variety of R&D topics: four experts primary R&D interests are glazing, one of these in addition is active in insulation and heat conduction. Another two are investigating insulation and heat conduction topics while one is focusing on electrochromics.

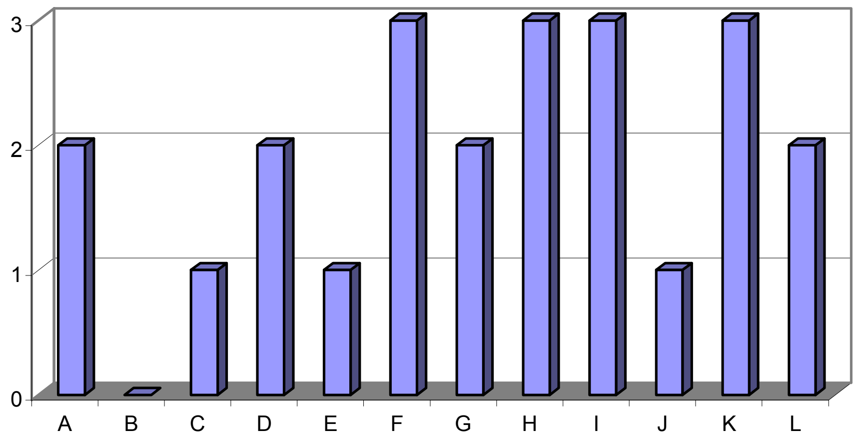
Insulation and Conduction Category most familiar with



As a result of the small population sample there is no clear leader for R&D focus, with no topic being researched by more than three of the seven experts. The "Other" category entries are:

- plasmon resonant nanoparticle doped polymers for spectral selective control, daylight capture and light piping without heat
- simulation of deposition processes

R&D Focus of Investigation



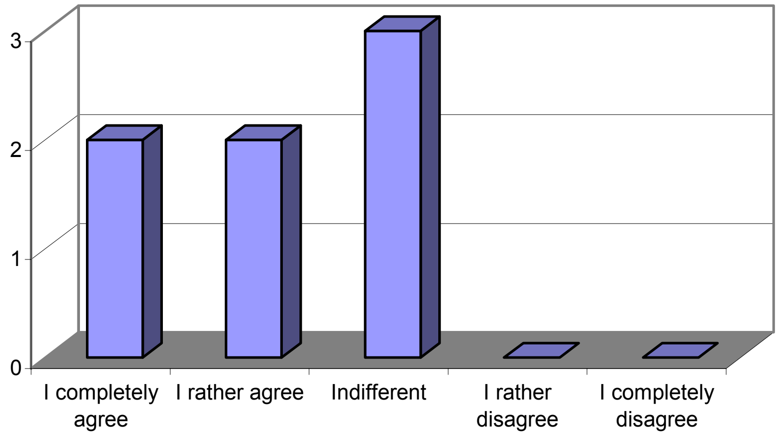
A. Porous materials with immobilised air or other gases
B. Managing "waste" heat by transferring it to electrical current
C. Improving heat conduction
D. Applying a reflective surface or coating onto a structure
E. Developing ultra low-density aerogels
F. Developing thermochromic smart glazing
G. Developing photochromic smart glazing
H. Developing electrochromic smart glazing
I. Developing lower cost alternatives to Indium-Tin-Oxide (ITO)
J. Reducing switching time for the colour change
K. Developing microstructured surfaces
L. Others

2.2.2 Nanotechnologies in heat insulation/conductance – Value Chain

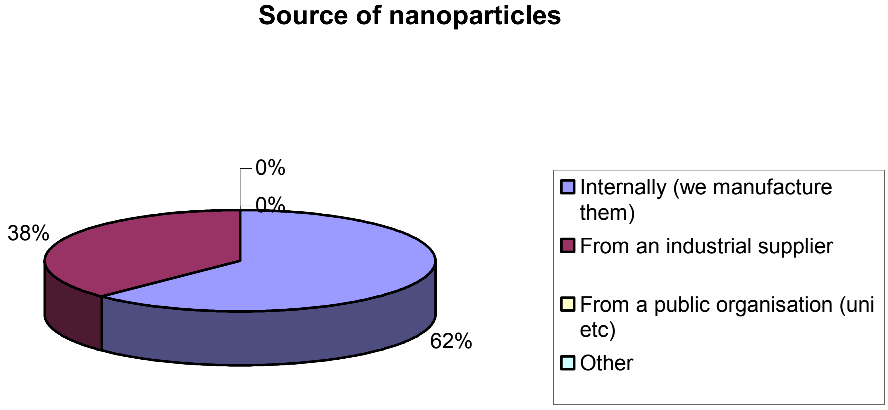
Production

Access to materials for R&D appears to be an issue with most of the experts who responded to the questionnaire. Four have frequent problems in finding nanoparticles to satisfy their R&D and/or manufacturing needs, and while three are indifferent to this matter, there is no-one who finds it easy.

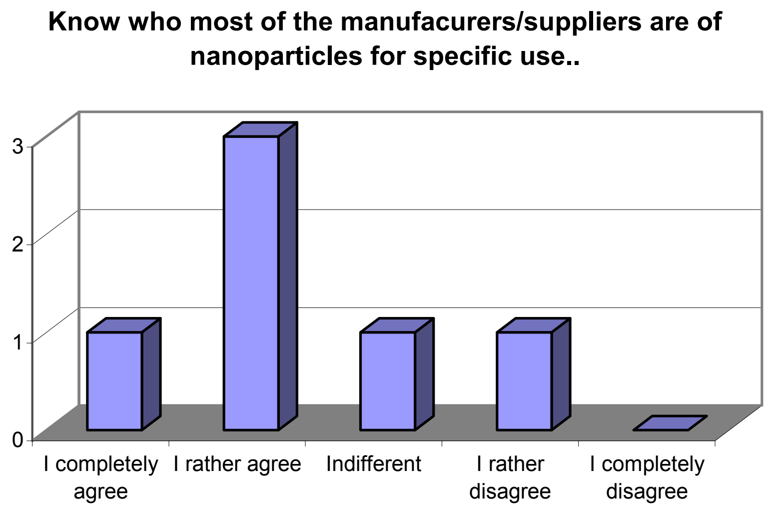
Frequent problems in finding nanoparticles?



This limitation is strange in light of the fact that five of the seven experts manufacture their own nanoparticles for their R&D, with three sourcing them from an industrial supplier. However given that this area is much closer to market applications, it may be that quantity and quality of the manufactured nanoparticles are the limiting factors.

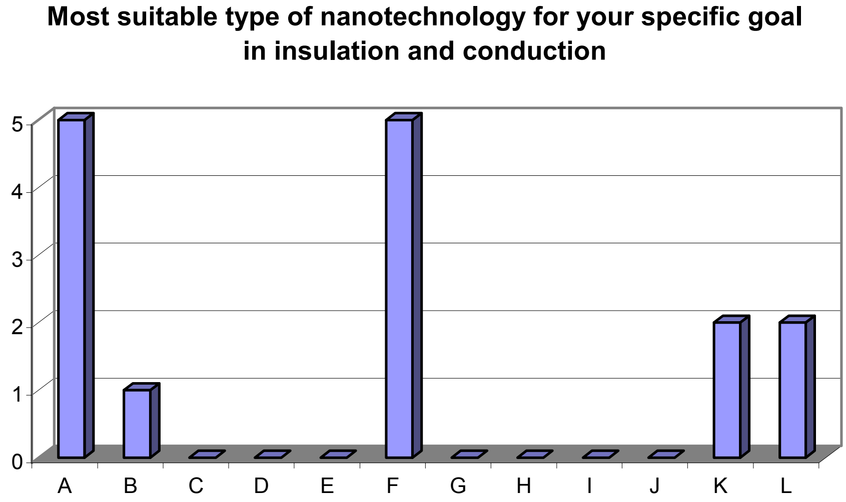


Given that most experts are of the opinion that they know the majority of manufacturers for their R&D materials, then the lack of a ready source is a serious potential barrier to continued R&D.



Functionalisation

Thin films, layers and surfaces and nanoparticles are the most extensively used materials for R&D applications, although two experts made use of nanocrystalline materials, one made use of carbon nanotubes, one of aerogels and one of nanocolumnar surfaces.



A. Thin films, layers and surfaces
B. Carbon nanotubes
C. Inorganic nanotubes
D. Nanowires
E. Biopolymers
F. Nanoparticles
G. Fullerenes
H. Dendrimers
I. Quantum wells
J. Quantum dots
K. Nanocrystalline materials
L. Others

Thin films and nanoparticles are expected to contribute the most to applications in heat insulation and conductance over the next decade.

2.2.3 Application

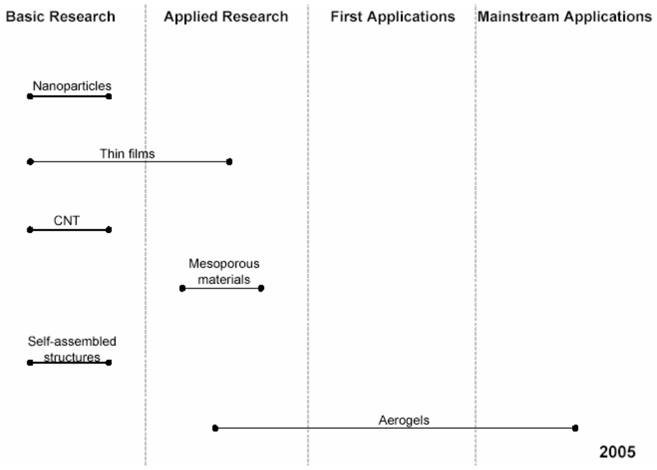
Expanding on this, experts were asked to identify the most important R&D topics to them and chart their progression over the next nine years, from basic R&D through to current applications. The definitions used for each stage in the development process are given below, and the charts describing this progression are on the following page:

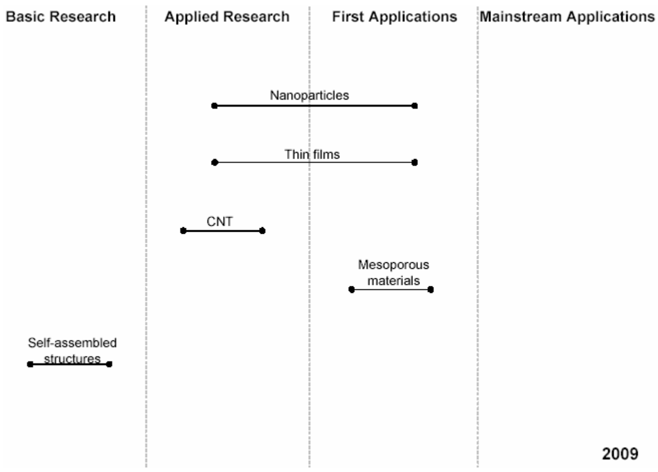
Basic R&D phase: applications in this phase have received the interest of one or more researchers in the world. Some applications might still be in early development, while others are tough to develop and need a lot of basic research to be understood. The object of basic R&D is to validate the original hypothesis. Various applications are currently in this phase.

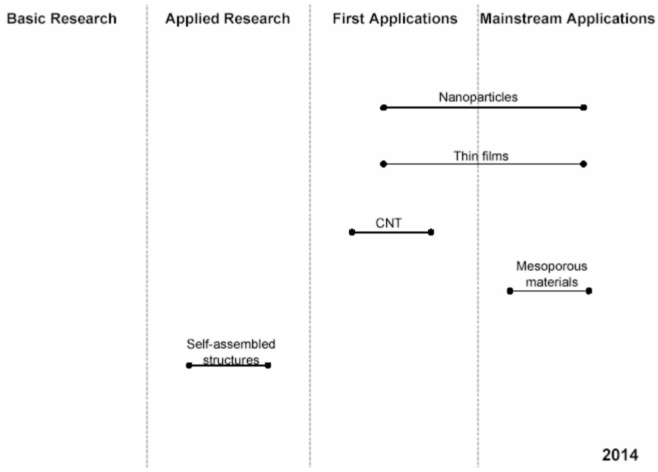
Applied R&D phase: after the hypothesis is validated, research typically (but not necessarily) moves from pure research labs to more commercial labs and companies. Applied R&D will eventually result in a proof of concept, a successful demonstration model. While the production issues might not have been solved yet, a successful prototype/model has been validated.

Product R&D phase (**first applications**): after demonstrator models and prototypes, initial, usually prohibitively expensive, small numbers of products may be produced. If these prove successful, companies will seek to enhanceproduction to gain market share. Generally at some point, demand increases sufficiently to offset the investment needed to start production. This phase ends at a point when feasibility proven and production is to start.

Production level and incremental research (**mainstream applications**): the final development phase, when production has reached significant numbers and research focuses on incrementally improving the products.

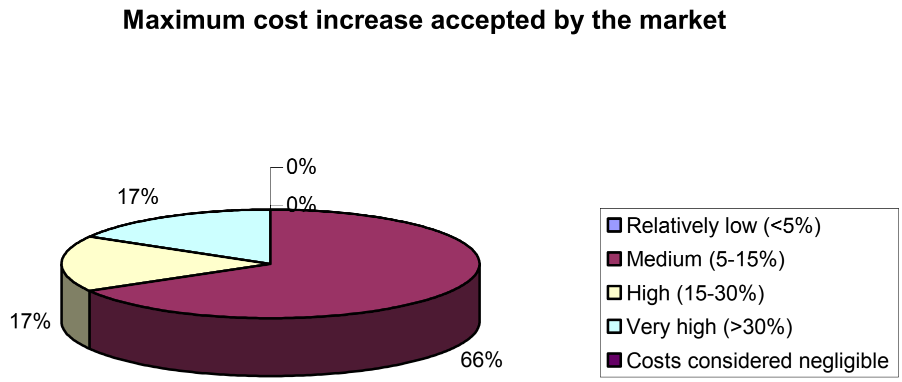






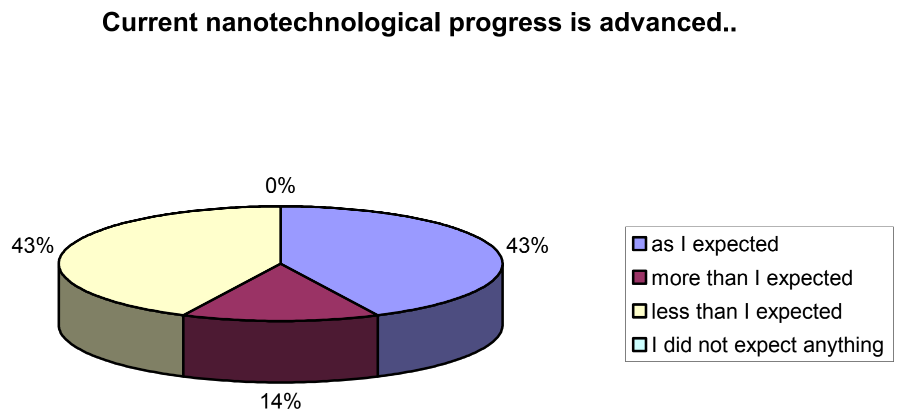
These limited results indicate that most of the experts expect nanoparticle and thin film research to develop into applications over the next nine years. These application areas include superhard materials and switchable coatings for glazing. Aerogels are well-established materials, with cost being the major consideration in their lack of general use up to now. The increase cost in energy however, has recently made them more attractive, with applications in glazing and pipelines (for natural gas), and R&D in polymer:aerogel composites.

There is no clear indication of the focus of basic R&D in 2009 and 2014. This may be because many of the materials undergoing basic development just now are expected to address current limitations and thus have significant impacts on products within the next decade, and it is therefore unclear what the next set of demands will be. Solving current material limitations means that these new materials can expect to command a medium to high price increase compared with existing technologies.



2.2.4 Retrospect

To place current and future R&D in perspective, experts were asked their opinion on how nanotechnologies had impacted thermoelectricity R&D over the past ten years. The general consensus of opinion was that progress has advanced less than was expected or as had been expected. Only one expert answered that it had progressed more than anticipated (see below).

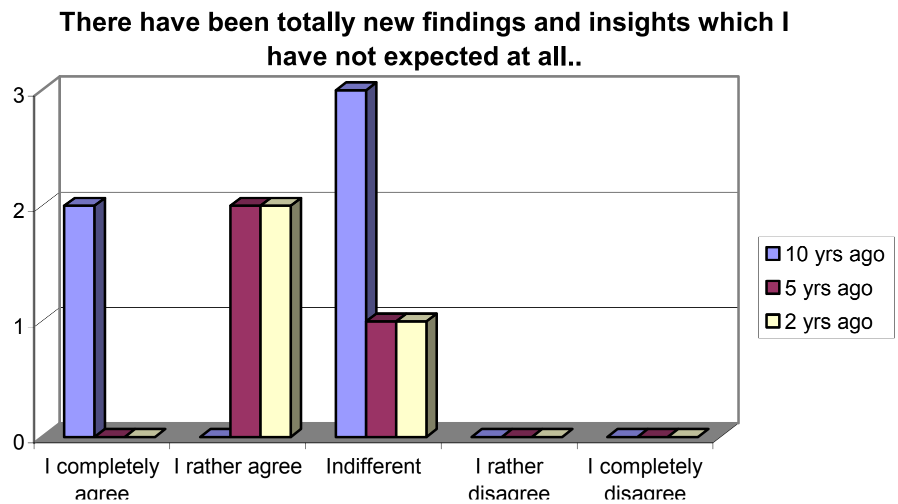


Following on from this the experts were asked if certain developments had arrived sooner than expected over the past ten years. Only four experts provided answers to this, which gives little indication to the consensus of opinion on the rate of R&D within heat insulation/conductance. Of interest are the topics picked out be the experts as appearing earlier than expected:

- dye-sensitized TiO_2 as an electrochromic
- nanoparticle-doped glazing products
- application of aerogels (which are relatively expensive) made favourable as a result of higher energy costs

- thin films on glass
- transparent scratch protection

The question of whether unexpected new findings and insights had appeared over the last ten years attracted a larger response with some experts agreeing this was the case, but none disagreeing.

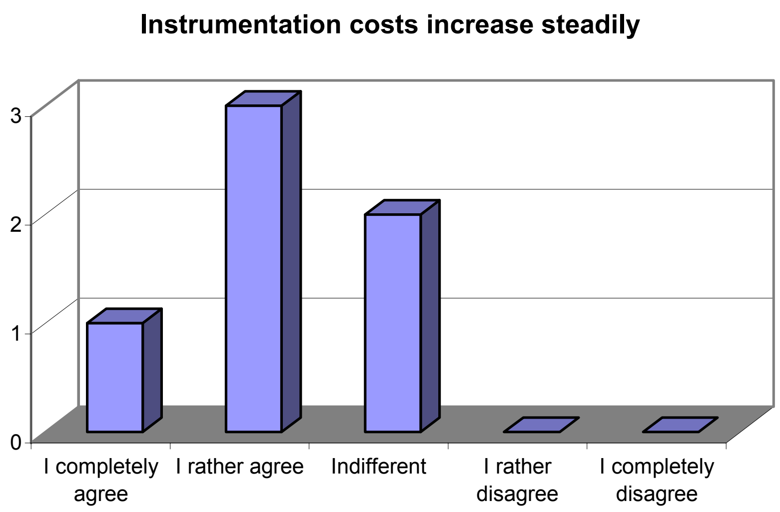


Examples included the thermal conductivity of carbon nanotubes, light distribution and transport systems, and thin films on glass.

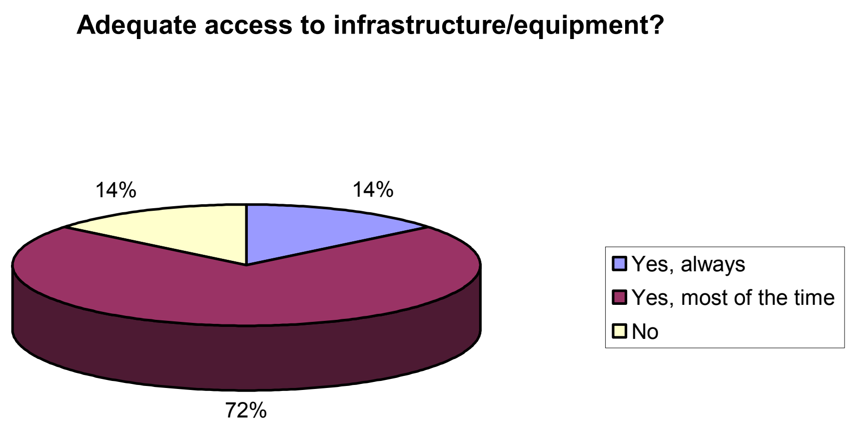
2.3 Non Technological Aspects

2.3.1 Infrastructure Requirements

Experts were asked whether the instrumentation costs for the manufacturing, characterization and manipulation of nanotechnologies in the application(s) areas of heat insulation/conductance have increased steadily. Four respondents thought that costs had increased and two were indifferent. No expert disagreed with the statement.

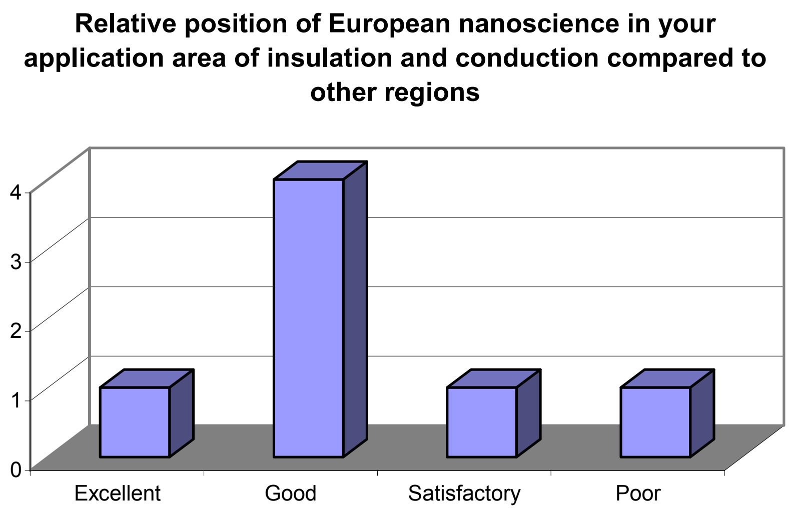


Adequate access to infrastructure/equipment for the performance of typical nanotechnology-related activities (including the use of both internal and external facilities through existing collaboration), does not appear to be an issue for R&D with only one expert finding difficulty.



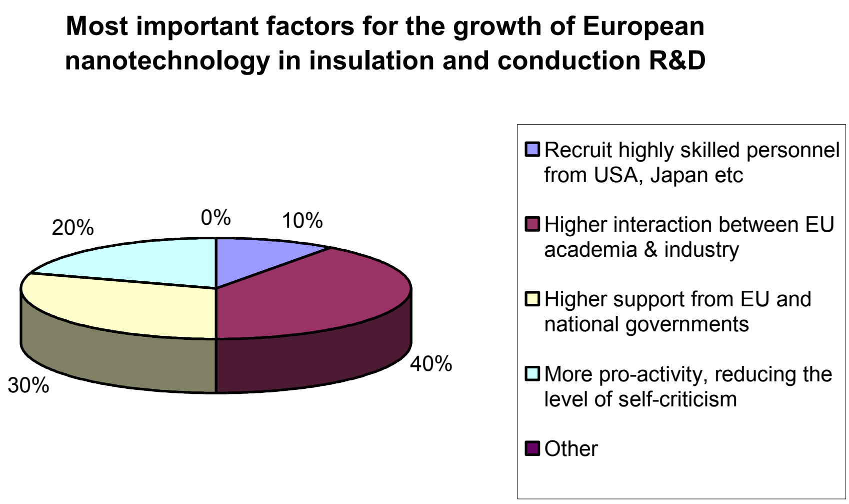
2.3.2 Economic Aspects

The insulation and conductance material industry is well established; so new technologies must primarily address increased efficiency per unit mass of material, or completely new applications such as smart glazing. European nanoscience which provides the input to these applications is seen to compare very favourably with other global regions, with only one expert of the belief that Europe is relatively poor compared to other world regions.



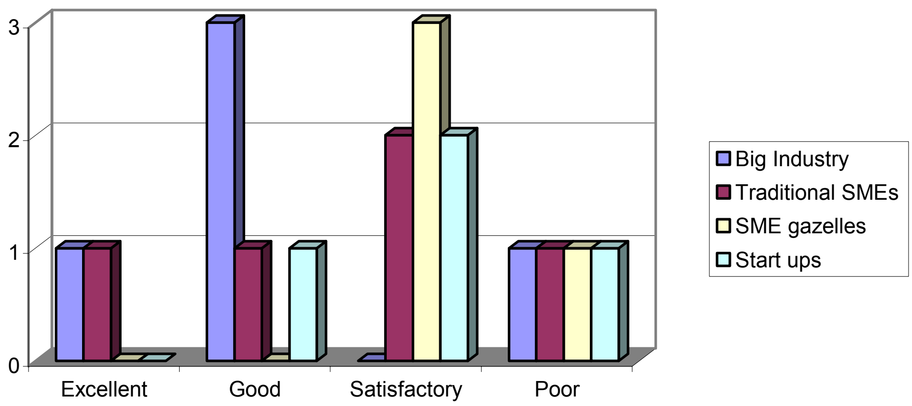
According to the experts, the most important factors for the growth of European nanotechnology in heat insulation/conductance during the next decade are higher support from the EU and national governments and higher interaction between EU academia and industry. Two of the industry experts thought that in addition to a higher interaction between academia and industry, that there should more pro-activity, reducing the level of self-criticism. In contrast only one expert thinks that Europe needs to recruit highly skilled personnel from other regions.

Experts were asked how the European Commission could contribute most to advancing state-of-the-art nanotechnology in their application areas. Six experts said this could be achieved by supporting more, smaller collaborative R&D projects. Specifically this would reduce bureaucracy and waste, and allow better selection of skills. No expert thought that fewer, bigger collaborative R&D projects would be better.



In contrast to other energy sectors, European nanotechnology industry in heat insulation/conductance is ranked relatively well compared with other global regions with only one expert of the opinion that it is poor at all levels. In fact European big industry is thought to be good or excellent compared with those in the US and SE Asia. This is further supported by the fact that five European companies are cited as being among the leaders in the world for nanotechnology applications in heat insulation and conductance.

Relative worldwide postion of European nanotechnology industry in insulation and conduction



Region	Company (number of citations by experts)
Europe	Saint-Gobain (3), Pilkington (2), Gloverbel, BASF, Scott Glass.
N. America	Guardian Industries (2), General Electric, IBM, Solutia, Cabot Corp., Aspen Aerogels, PPG.
Asia	Asahi Glass (3), Sumitomo.

2.4 Conclusions

European nanoscience and nanotechnology industries in the heat insulation and conductance sectors appear to be competing well on the international arena according to the limited response received. In fact, in stark contrast to other energy sectors, big industry in Europe is seen as performing well with respect to other regions, with only one expert stating that it was poor. It should be noted however, that most of the answers focused on glazing applications.

Nanotechnology is expected to play a major role in heat insulation and conduction applications by 2009. This will be mainly due to novel properties, i.e. added value, rather than decreasing costs compared with existing technologies. In fact, all experts thought that at least a medium increase in relative costs would be tolerated by the markets. Nanoparticles and thin films are expected to be the major contributor to this, with applications in areas such as electrochromic (or switchable) coatings for glazing products.

According to the experts, within the next ten years the major nanotechnological challenges in heat insulation/conductance R&D will include:

- stabilizing electrochromic systems.
- preparing photoelectrochromic windows.
- routine uniform incorporation of nanoparticles in support matrices.
- large scale manufacture of specific nanoparticles in specific shapes.
- lowering the cost of aerogels.
- controlling nanoporosity.
- developing smart environment-responsive glazing.
- developing superhard materials for heat-insulation coatings.

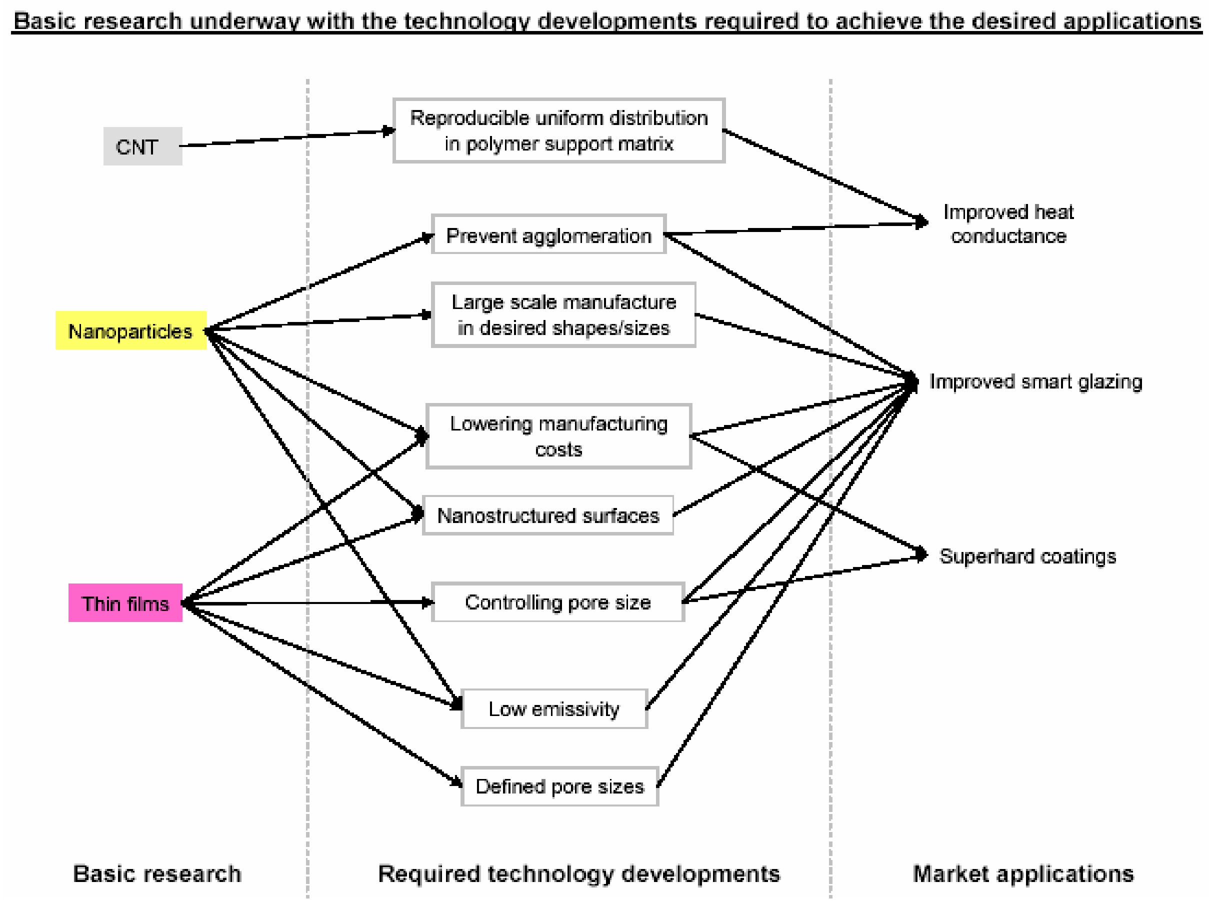
Already much of the R&D is in the applied phase with the main challenges, foreseen for the coming decade, in the further development of coating materials in terms of stabilisation and their mass-production (rather than identifying new materials).

Although access to infrastructure is acceptable for most, some of the barriers to achieving these goals could include:

- access to supplies of nanoparticles (more experts experienced difficulty in sourcing nanoparticles for their R&D than did not)
- rising instrumentation costs

In terms of the resolution of these issues, one possibility which has wide support (in all energy sectors) is the funding of small collaborative projects. Within these settings industrial partners could play the role of developing materials (and production methods), that are tested in different experimental set-ups by the academic partners.

The diagram on the following page summarises areas of research, their eventual applications and the technological developments which will be needed to achieve these.



Appendix

Fifteen experts were asked to take part in the questionnaire of which seven (one each from Australia, Germany, Japan, Slovenia, Sweden, UK and USA) completed and returned the questionnaire. Four experts were from academia and three from industry.

Prof. Geoff Smith, University of Technology, Sydney, Australia	Dr. Volker Sittinger, Senior Researcher, Fraunhofer IST, Germany	Prof. Hidehiro Kamiya, Tokyo University of Agriculture and Technology, Japan
Prof. Boris Orel, Head of Dept., National Institute of Chemistry, Slovenia	Thomas Liljenberg Programme Manager, ABB, Sweden	Simon Hurst, Pilkington, UK
Nirmalya Maity, Director Aerogel Business R&D, Cabot Corp., USA		