SMART

Specific Support Action

Materials powering Europe

Energy Workshop, April 2006

Imprint

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Printed by: Grafische Medien, Forschungszentrum Jülich GmbH

March 2007

SMART stands for 'Foresight Action for Knowledge Based Multifunctional Materials Technology'. It is a Specific Support Action (SSA) of the European Commission within FP6. SMART started in April 2005 and will analyse, within 2 years, the most relevant research fields in materials science.

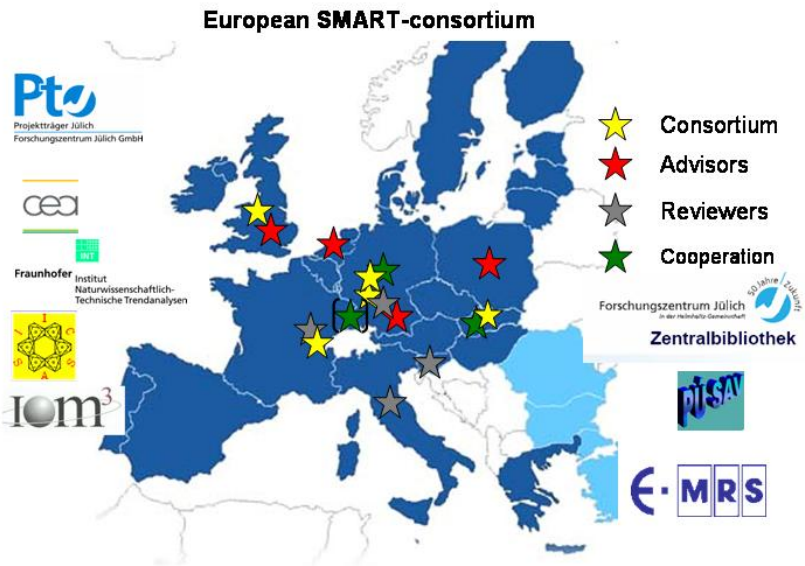
SMART objectives are:

- Improvement of European R&D-Position
- Improving public awareness especially of tax payers
- Enabling the further development of ERA.

These objectives are being achieved by:

- Identification of materials research hot spots for the future
- Mapping of European materials research activities
- Development of roadmaps
- Analysing foresight studies
- International benchmarking.

The following diagram shows the members of the SMART consortium.



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1.

EXECUTIVE SUMMARY

SMART is a Specific Support Action (SSA) of the European Commission within FP6, and as part of an exercise to look at the future materials needs for energy generation and usage, a workshop was held to engage experts in the field to help produce a roadmap specifying the research requirements for:

- Materials for Energy Efficiency (primarily 'generation', not addressing consumption/energy usage)
- Materials for Sustainable Energy Technologies.

This workshop endorsed previous findings and identified the following actions and recommendations:

Materials for Energy Efficiency

- Innovative coatings technology is an essential way to improve efficiency, for stationary turbine components as well as rotating parts.
- High temperature alloy development.
- New battery storage materials are needed in order to improve storage.
- Heat losses are currently far too high. Waste heat must be used much more efficiently.
- Multi-scale modelling in materials technology should be progressed to reduce timescale from an idea to conception. A database to help this should be provided.
- There is a great deal of scope to improve communications and networking between all interested parties. This would help inform governments. It would also enable transfer of information across the different sectors of the Energy Industry where some of the problems and issues are common.
- Materials community working on materials topics on fossil plants should communicate with those in nuclear.
- Emission free fossil fuel power plants are a requirement. Better public perception of the issues should be provided. Oxygen separation membranes and associated corrosion problems need to be addressed, and re-use of strategic materials and gas emissions should be undertaken.
- A strategic plan for material supply is needed, along with new materials concepts for energy storage.
- Scale up / integration / implementation from lab to production of intelligent systems is required.
- There is an identified need for new sealing and joining systems, with smart, reactive coatings.
- Regulatory / fiscal incentives for the production of CO_2 free energy are imperative.

Materials for Sustainable Energy Technologies

- Mass production would be most beneficial to bringing the costs down for alternative sources of energy generation.

- Better storage and transport of energy should be sought. It is recommended that improvements in superconductors and micro-turbines for distributed generation should be examined. In addition, advances in high energy density storage are needed.

- Current funding is channelled towards 'political' topics; real issues that will help Europe should be followed, and less risk aversion would enable step-leaps in progress.

- The aim should be to produce materials that can withstand 2000°C, and other extreme conditions.

- Costs are currently too high for new systems to be competitive. Functional materials that are highly efficient and are available on a large scale are a requirement. Coatings need to last much longer, and fuel-flexible plants should be explored.

- There are few incentives for the provider, or user, of energy to change from current supplies. Energy legislation or tax concessions should be considered for the introduction of new ways of energy generation.

2.

CONTRIBUTORS

The following people attended a meeting during the Institute of Materials, Minerals and Mining Congress 2006 on Friday 7th April 2006 to prepare a roadmap in Materials for Energy Efficiency and Sustainable Energy Technologies:

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3.

METHODOLOGY

The methodology used for roadmapping is summarised in Appendix 8.1, following the procedures typically used for other roadmaps that have been produced.

For a typical roadmapping session, experts, in groups of around five, are asked to provide their thoughts and opinions for the four main stages of the roadmapping process:

- Where are we now?
- Where do we want to be?
- What is stopping us getting there?
- What needs to be done to overcome the barriers?

For each stage, large hexagon *Post-its* are used to gather each input. These are then clustered under common topics as a spokesman from each group presents their findings. This draws comments from the rest of the participants and generally arrives at a consensus of opinion.

Using adhesive stickers, priorities are given to what are considered the most important issues for the second stage of the roadmapping process, enabling a key priority list to be established for subsequent steps.

The final outcome is a list of priority items that need action in order to enable the industry to progress in a more dynamic and competitive manner.

As with other roadmaps, once this first edition is produced, comments are sought from others in the field, so that ownership comes from the entire community.

For this roadmap, the first two stages of the roadmapping procedure (*Where are we now?* and *Where do we want to be?*) were covered by presentations from experts in particular fields.

4.

CURRENT TRENDS AND FUTURE DIRECTIONS

A number of recent publications have considered the future trends related to energy roadmaps. By way of introduction, these are summarised for reference in Appendix 8.2.

4.1 Materials for Energy Efficiency

Professor Lorenz Singheiser, Director of the Institute for Materials and Processes in Energy Systems, at the Forschungszentrum Jülich in Germany, gave a comprehensive presentation on *Present and Future Developments in Materials for Energy Efficiency*. Some of the main points are captured below.

The materials challenges for energy efficiency are:

- Gas turbines
- Boilers
- CO_2 capture (through membranes or nanoporous materials)
- Solid oxide fuel cells (SOFC).

The short term need is to reduce energy usage by being more efficient, and to produce less CO_2. The best current efficiency of coal-fired energy generators is 55%, and although CO_2 emissions have been reduced by 45% over the last 25 years, there is a great deal of scope for further reductions.

Future trends will see changes in:

Gas turbines

- Gas turbine blades
  - Ceramics
  - Reinforced Aluminides
  - Silicide based
- New measurement techniques for mechanical properties of coatings
- Higher temperature ceramic systems (> 1400°C) especially for industrial gas turbines
- Better bond coatings
  - More modelling for improved coatings and life prediction
- High strength and high temperature materials
- Adaptive coatings e.g. self-healing
- Erosion resistance
- Rotor forging components
  - Moving to nickel based alloys and other high temperature alloys.

Boilers

- Boiler and steam turbine materials
  - Conditions will be > 700°C at 350 bar until 2015.
  - Requirements for materials – need austenitic steels for high temperatures, with Cr steels decreasing. There are solutions for up to 600°C. Predictions are based on trial and error
  - Need a better understanding of microstructures, where the key challenge is to understand the microstructure during all stages.

CO_2 capture

- Combustion technologies
- Gasification

- Membranes – research required for membrane technologies and Oxyfuel process.

Fuel Cells

- The problems are high cost, sealing, thermal cycling, corrosion, and assembly technologies and reliability.

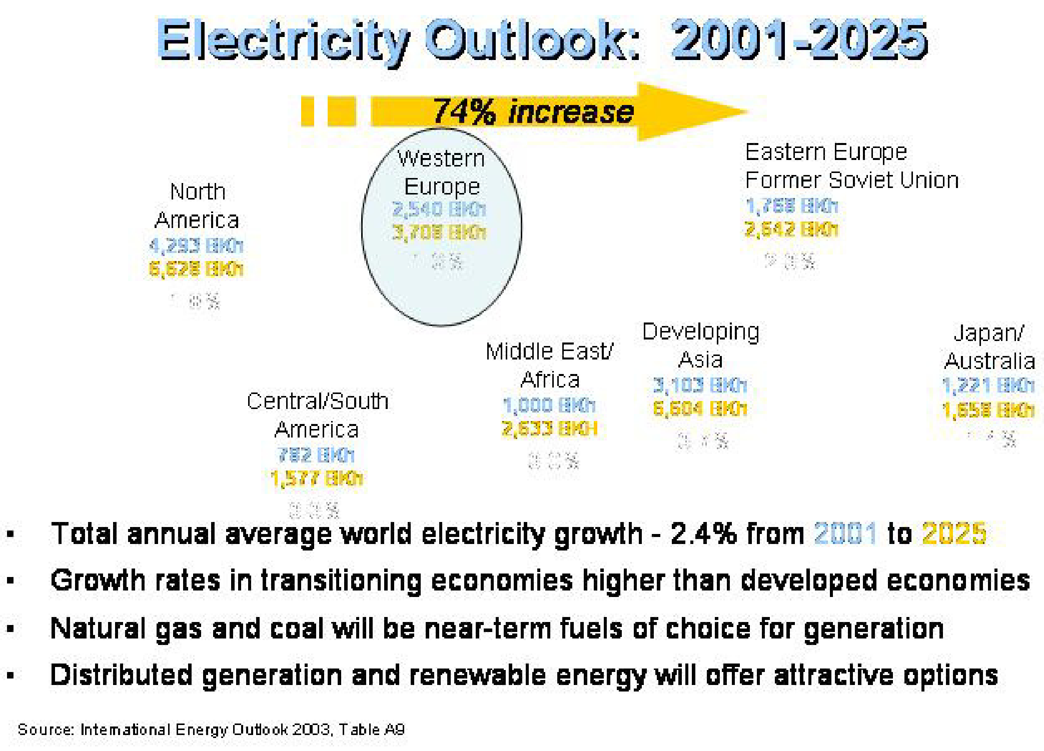
4.2 Materials for Sustainable Energy technologies

Professor John Kilner, of the UK Energy research Centre, based at Imperial College (www.ukerc.ac.uk), gave a presentation on *Functional Materials for Sustainable Energy Technologies*.

The challenges for the future energy scenario with respect to functional materials were given as:

- Clean non polluting transport
- CO2 emissions; Climate change
- Security of supply
- Ageing central generation fleet; Conventional + Nuclear
- Distributed generation
- Renewables and intermittency; storage
- Fission new build
- Fusion
- Hydrogen Economy.

The demand for electricity will see a massive increase over the next 20 years. Growth in different regions of the world was illustrated:

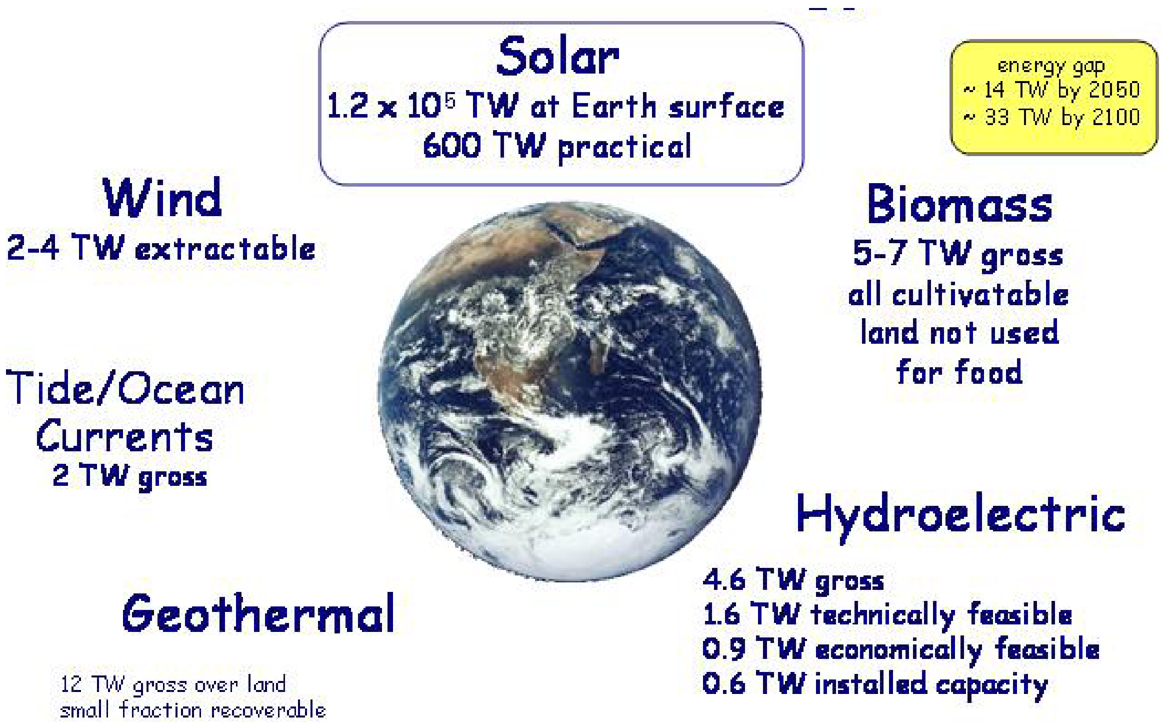


Technology based solutions to the problems are:

- Energy efficiency
- Lifetime extension
- Renewable energy

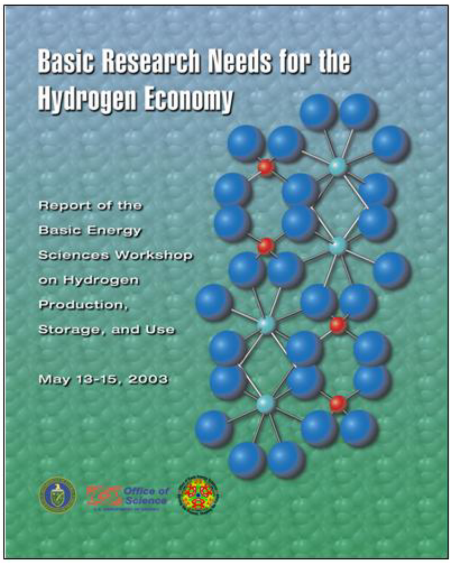
- Non-polluting transportation fuels
- Separation and capture of CO_2 from fossil fuels
- Next generation of nuclear fission and fusion technology
- Transition to smart, resilient, distributed energy systems coupled with pollution-free energy carriers, e.g. hydrogen and electricity.

The following slide presents relative data on renewable energy:



In addition to presenting data on fuel cells, additional information on solid state lighting for buildings was shown. There are potential opportunities and annual energy savings because LEDs and OLEDs have the potential to replace incandescent and fluorescent lighting in a broad variety of end-uses. A key difficulty that LED lighting faces is that it is inherently monochromatic, but several methods are being researched to produce white light. Current uses are in traffic lights.

For superconductors, the potential opportunities and annual energy savings are high, with reduced transmission losses (typically 7%-8%) by 20% for cryogenics, and increased efficiency of generators and motors. High-temperature superconductors can significantly increase the capacity of transmission cables, and can also enable fault finding, better energy storage, and provide oil-free, more efficient transformers.



For the Hydrogen Economy, a recent workshop was held, at Oak Ridge National Laboratory to develop an international strategic plan entitled *Transforming Our Energy Future: Advancing the Role of Science and the Critical Connections with Applied Energy Programs*.

The report identified high priority research areas as:

- Novel materials for hydrogen storage
- Membranes for separation, purification, and ion transport
- Design of catalysts at the nanoscale
- Solar hydrogen production
- Bio-inspired materials and processes.

The following point was made regarding the development of new materials:

'Of particular importance is the need to understand the atomic and molecular processes that occur at the interface of hydrogen with materials in order to develop new materials suitable for use in a hydrogen economy. New materials are needed for membranes, catalysts, and fuel cell assemblies that perform at much higher levels, at much lower cost, and with much longer lifetimes. Such breakthroughs will require revolutionary, not evolutionary, advances'.

Professor Kilner looked at the 'grand challenges' for energy and listed the highest priority technology barriers as:

- Solar PV increase efficiency >50% at $100/m^2
- Clean coal with CO_2 capture - affordable and environmentally safe
- Multimode storage of energy; electricity (battery) and heat
- Step change in catalysis (bio and non-bio)
- Low loss transmission and distribution
- Full system approach to industrial processes
- Vehicle light weighting cheap and efficient materials.

The science opportunities were also listed for nano-sciences / materials:

- Interfaces
    - Batteries
    - Fuel cells
    - Solar cells
    - Catalysis
- Leading to innovative materials
- Atomic scale engineering
- Nano-biology
    - Organic/inorganic interfaces
    - Biogeneration of semiconductor materials
- Biomimetic self-organizing/ healing/ diagnostic
- Multi-scale (space and time) modeling integrated approach
- Predictive modeling.

Dr David Gooch gave a presentation on *Materials Issues in Renewable Energy Power Plants*. The talk covered:

- Wind power
- Tidal and wave power
- Hydropower and estuarine barrages
- Waste to energy
- Biomass
- Geothermal
- Solar.

<u>Wind power</u>

The characteristics of a 3.6MW wind turbine machine are that it has 52m blades, which require high strength / weight ratio; stiffness; fatigue strength; good corrosion, erosion and stress corrosion resistance; resistance to UV exposure; good impact resistance; and low cost.

Current materials used are dominated by:

- GRP (glass reinforced plastic)
- CFRP (carbon fibre reinforced plastic) - emerging but expensive - used for internal spars of some 3MW machine blades
- Wood / epoxy laminates strengthened by carbon fibre - used in one type of 1.5MW machine.

GRP development areas are:

- Effect of spectral loading on fatigue life
- Environmental degradation – e.g. effect of moisture absorption by matrix leading to surface crazing
- Scaling results from test coupons to full size components
- Joining techniques –
  - to allow blades to be transported in sections
  - to join composites to metals
- NDE and life assessment.

Tidal and wave power

Greater than 100years life is requirement, but concrete steel reinforcement corrosion is a problem for the following reasons:

- chloride attack destroys passive layer normally present in alkali conditions
- carbonation of concrete produces acid conditions

Possible measures are cathodic protection, polymeric coatings, or corrosion inhibitors in concrete.

Hydropower and estuarine barrages

Hydro turbine materials issues are:

- Corrosion / stress corrosion /corrosion fatigue
  - Low cost C and C-Mn steel adequate for many components
  - Extensive use of stainless steels for critical components
- Silt erosion in high solids burden waters
  - coatings - HVOF tungsten carbide, thermally sprayed ceramics
- Cavitation erosion
  - thermal shock due to collapse of vapour bubbles formed when fluid pressure becomes less than vapour pressure
  - minimised by flow design and materials /coatings selection.

Waste to energy

Materials issues are:

- Superheater tube corrosion -steam conditions, and hence efficiency, are limited by superheater corrosion to typically 400C, 40bar
- Target of 520C, 100 bar steam set in EU programme
- Need low cost tube to replace carbon steels used
  - high Cr, Ni based with up to 8% Mo seem best
  - main candidates Alloy 625 based - expensive
  - coatings / claddings
    - Alloy 625 - some doubts about performance in final superheat stages
    - Flame sprayed or HVOF Fe-35Cr-5Si may be cheaper and better.

Biomass

Dr Gooch identified the technologies as:

- Combustion
  - grate firing / fluid beds, typically 20-25% efficiency
  - steam generated drives a steam turbine - typically < 20MWe
  - co-combustion with coal in utility boilers becoming favoured option for wood fuels
- Gasification combined cycles
  - small stand alone plants or possible co-gasification in large integrated coal gasification plants (IGCC)
  - potential for > 35% efficiency in stand-alone plants, greater in co-gasification.
  - demonstration projects in EU and USA.

Materials issues for biomass combustion were given as:

- corrosion highly fuel specific, eg alkali chlorides from straw
- no consistent correlation of corrosion rates with Cr, Ni content
- reduced by co-firing - S in coal produces sulphates, which are less corrosive than chlorides
- reduced by injection of ammonium sulphate – converts alkali chlorides to the less corrosive sulphate.

Materials issues for biomass gasification are:

- corrosion potentially more severe than for combustion because of highly reducing conditions
- main chambers are refractory lined
- little downstream heat recovery possible because of corrosion of heat exchangers
- potential for gas turbine corrosion problems from fuel combustion products, trace elements, tars, ash etc – need for (hot) gas cleaning.

<u>Geothermal</u>

No details were given in view of the limited opportunities in Europe.

<u>Solar</u>

The solar thermal technologies were listed as:

- All technologies use reflective collector systems to concentrate light onto receiver
- Receiver may be a heat exchanger or engine
- HX working fluid may be mineral oil or molten salts or metals
- Main materials issues
  - corrosion fouling, abrasion etc of collectors
  - corrosion of heat transfer systems.

For solar PV, the materials issues were tabled:

Component	Materials issues – 20 year design lives
Support structures, Tracking systems	Strength / weight ratio Corrosion resistance Cheaper lightweight structures needed
PV modules – usually laminated and encapsulated in ethyl vinyl acetate, with glass covers	Electrical performance is main development area BUT environmental resistance requirements are also demanding, e.g. Thermal/humidity/freeze cycles: –45 to +85C; UV exposure, hot spot endurance; hail resistance, wind loads to 225km/h
Adhesives for module attachment	Endurance, Elasticity retention, Ease of removal

Dr Gooch's final slide summarised the situation for materials:

- Structural materials issues are not generally critical to the initial introduction of renewable energy technologies. However economic viability and market penetration are often dependent upon materials developments to increase efficiency, decrease maintenance costs and increase operational life
- Structural monitoring and life assessment will become increasingly important as plants age.

5.

BARRIERS TO PROGRESS AND POSSIBLE SOLUTIONS

Following the presentations which set the present and future scenes for Materials for Energy Efficiency and Sustainable Energy Technologies, the experts (industrialists, academics, users and suppliers) gathered for this Workshop were asked for their views and experiences, in order to carry out the next stages of the roadmapping exercise - *"What is stopping us getting to the vision?"* and deciding *"What needs to be done to overcome the barriers?"*.

Using yellow Post-its for the barriers and blue Post-its for the actions, the panel arrived at the clustered topics shown in Appendix 7.3.

These are tabulated below:

5.1 Materials for Energy Efficiency Section

COATINGS		
Issues	**Barriers**	**Next Steps**
Extreme improvement of energy efficiency through significant operating temperature increase (above 700°C)	• Insufficient knowledge of coating technologies generally and especially at high temperatures	• Innovative coatings technology for stationary turbine components

STORAGE		
Issues	**Barriers**	**Next Steps**
Improvements needed to store energy more efficiently	• Current limitations of energy storage, for transport and transmission, not well understood or accepted • Present battery materials not particularly efficient	• Need new battery storage materials to improve storage

HEAT RECOVERY		
Issues	**Barriers**	**Next Steps**
Use the waste heat efficiently	• Current heat losses too high	• Improve efficiency of usage

MODELLING		
Issues	**Barriers**	**Next Steps**
Near perfect lifetime and performance modelling- 50% reduction in R&D time and implementation	• Insufficient ability and lack of data to model (low status of theoretical work)	• Multi-scale modelling in materials technology should be progressed to reduce timescale from an idea to conception • Provide database

INFRASTRUCTURE / NETWORKING		
Issues	**Barriers**	**Next Steps**
Improve communications and networking	• Lack of co-ordination between interested parties – industry, academia and government • Little technology transfer across different sectors of the energy industry • There is a lack of an energy policy • Risk analysis not taken into account	• There should be government funding to help draw scientists from other disciplines to solve problems (e.g. between mathematicians and materials scientists) • Encourage clustering, co-operation, networking and sharing ideas • Provide a forum for cross-sector groupings of the entire supply chain to progress energy efficiency • Provide central directory / database of experts, and material properties, to encourage networking between different skill bases • Explore possibility of registration for quality, etc.

EFFICIENCY		
Issues	**Barriers**	**Next Steps**
Enable hydrogen economy by revival of nuclear technology	• Reluctance to accept nuclear within society	• Materials community working on materials topics on fossil plants should communicate with those in nuclear

ENVIRONMENTAL		
Issues	**Barriers**	**Next Steps**
Public & political perceptions – need emission free fossil fuel power plant	• Legislation and opinions are a factor • Lack of will, funding and time • Need efficient O_2 separation membranes • There is a barrier to removal of CO_2 and NO_X	• Provide better public perception of the issues • Oxygen separation membranes – associated corrosion problems • Re-use of strategic materials and gas emissions

ENVIRONMENTAL / TECHNOLOGY		
Issues	**Barriers**	**Next Steps**
European freedom energy engineering (recycling)	• Insufficient knowledge	• Strategic plan for material supply • New materials concepts for energy storage

KNOWLEDGE / TECHNOLOGY		
Issues	**Barriers**	**Next Steps**
Making structural components, in energy,	• Lack of knowledge	• Scale up / integration / implementation from lab to

technology smart – energy efficiency		production of intelligent systems
Advanced sealing for zero loss	• Loss of energy through gaps	• Advanced sealing techniques required • Smart / reactive coatings needed
Joining of dissimilar or similar materials for modular construction	• Lack of knowledge	• Research work needed

5.2 Materials for Sustainable Energy Technologies Section

COST		
Issues	**Barriers**	**Next Steps**
Significant reduction in costs is essential	• Alternative energy sources are not cost effective at present	• Mass production will bring the costs down

STORAGE & TRANSPORT		
Issues	**Barriers**	**Next Steps**
Improvements needed to store and transport energy more efficiently	• Present methods are inefficient for both transport and storage	• Seek improvements in superconductors and micro-turbines for distributed generation • Make advances in high energy density storage – supercapacitors

FUNDING		
Issues	**Barriers**	**Next Steps**
Funding is essential but it should be directed at real problems	• Current funding is channelled towards 'political' topics • Balance of funding to existing and new ideas is based on low risk	• Real issues that will help Europe should be followed • Less risk aversion would enable step-leaps in progress

EXTREME ENVIRONMENTS		
Issues	**Barriers**	**Next Steps**
Materials for 2000°C is the goal	• Limited materials for fusion • Little exchange of information between different sectors of the energy industry	• Aim to produce materials that can withstand 2000°C • Ensure more communication between sectors with different means of energy generation

SKILLS		
Issues	**Barriers**	**Next Steps**
Improve communications, knowledge transfer and networking	• Much knowledge has been lost • Insufficient networking and awareness	• Ensure knowledge is managed and disseminated better • Improve networking and awareness

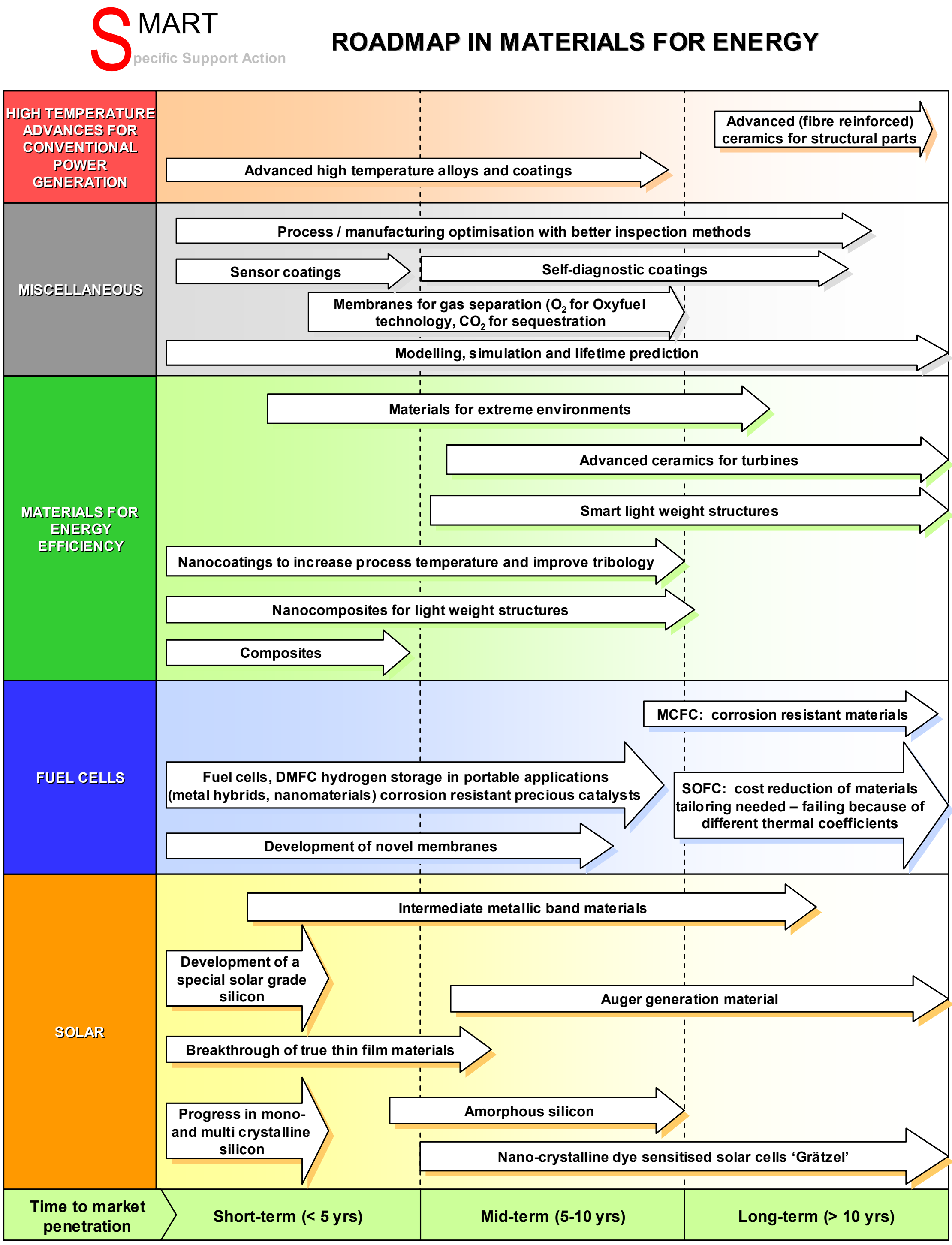
TECHNOLOGY		
Issues	**Barriers**	**Next Steps**
Reduce costs and improve performance	• Costs currently too high for new systems to be competitive • Biomass usage is limited by lack of supply and corrosion problems	• Need functional materials that are highly efficient and are on a large scale • Optimise longevity by use of better coating materials • Provide fuel-flexible plants • Establish plants that are able to co-fire (crop market)

LEGISLATION / REGULATION		
Issues	**Barriers**	**Next Steps**
Encouragement should be provided to allow the introduction of new technology	• Fuel pricing uncertainty is discouraging for new methods of generating energy • There are few incentives for the provider or user of energy to change from current supplies • Requires CO_2 pricing incentive for zero emission technologies	• Energy legislation or tax concessions should be considered with the introduction of new ways of energy generation

6.

ACTIONS / RECOMMENDATIONS

The workshop has confirmed many of the findings from a previously produced roadmap. The roadmap is summarised in the diagram shown below:



This workshop identified the following actions and recommendations:

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Materials for Sustainable Energy Technologies

- Mass production would be most beneficial to bringing the costs down for alternative sources of energy generation.
- Better storage and transport of energy should be sought. It is recommended that improvements in superconductors and micro-turbines for distributed generation should be examined. In addition, advances in high energy density storage are needed.
- Current funding is channelled towards ‘political’ topics; real issues that will help Europe should be followed, and less risk aversion would enable step-leaps in progress.
- The aim should be to produce materials that can withstand 2000^{o}C. Other sections of the Energy Industry should be consulted, and not just on this issue.
- Costs are currently too high for new systems to be competitive. Functional materials that are highly efficient and are available on a large scale are a requirement. Coatings need to last much longer, and fuel-flexible plants should be explored.
- There are few incentives for the provider, or user, of energy to change from current supplies. Energy legislation or tax concessions should be considered for the introduction of new ways of energy generation.

7.

APPENDICES

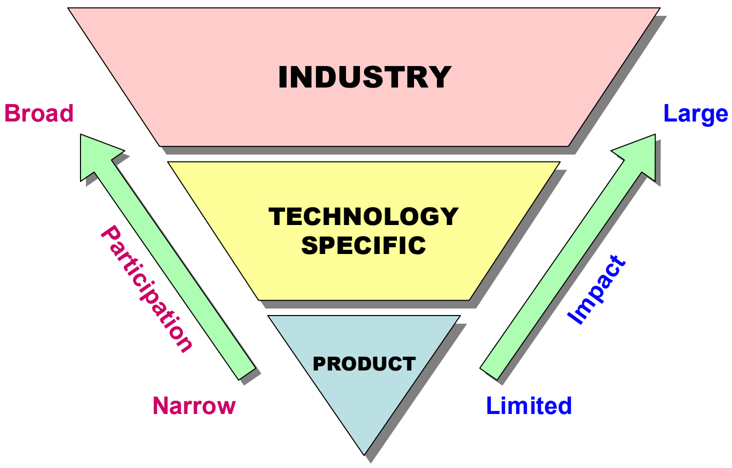
7.1 Methodology for Roadmapping

What is Roadmapping?

Based on a Foresight model, roadmapping is a high-level planning tool to help both project management and strategic planning in any technically-based establishment, whether in academia or industry.

Motorola first coined the word roadmapping in the seventies, but only recently has it been widely adopted by both individual companies and industry sectors as an essential part of their future growth. Figure (i) summarises the types of roadmaps that have already been produced. They can be for industries such as "glass" and "petroleum", or for specific technologies such as nanomaterials, biocatalysis, etc. Some roadmaps have been produced just for single product areas.

Figure (i): Types of roadmaps

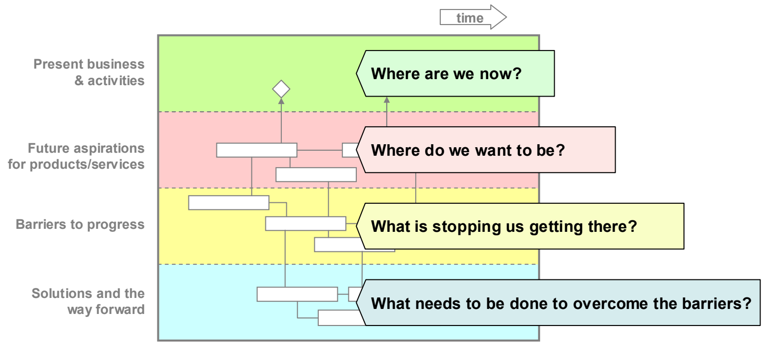


How are the Roadmaps produced?

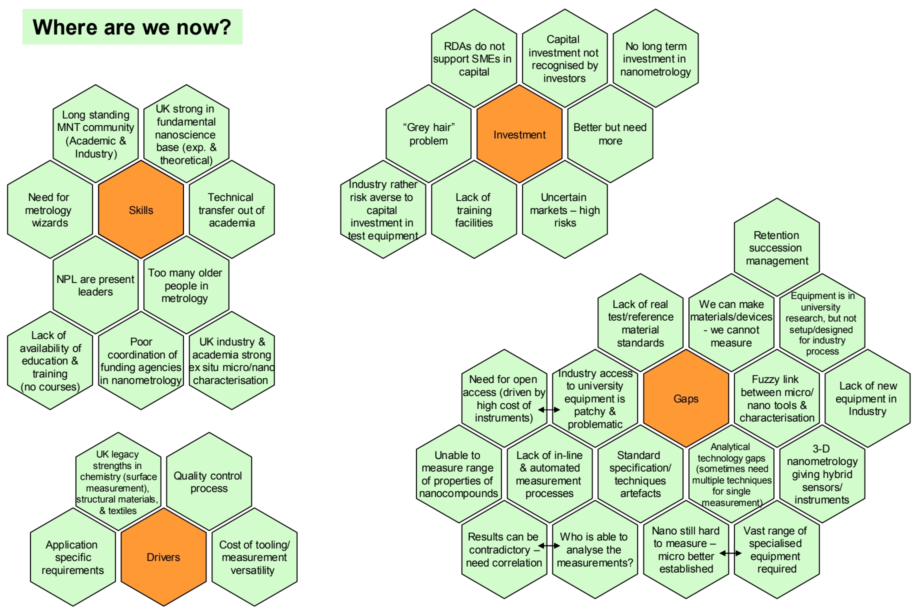
The process gathers together groups of commercial as well as technical experts, and takes them through the four stages that are shown in Figure (ii). The participants need to have sufficient information about the markets and the business to say where the topic under consideration is at the present time. The first step is to agree what the present situation is, and then to move on to provide a vision of where they see things going in the future - where they want to be during the next 20 years.

The third stage is to determine what the barriers to achieving the objectives and goals are. Finally decisions and proposals need to be made to enable the barriers to be overcome. These are arranged over a timescale, with short-term (0 to 3 years), medium-term (3 to 10 years), and long-term (> 10 years) goals.

Figure (ii): Stages in the Roadmapping exercise



Hexagon shaped *Post-its* (colour coded for each stage) are used to gather the participants' thoughts for each step. These are then grouped into topics, and a typical example is shown in Figure (iii). When a consensus is reached regarding the conclusions, "dot" stickers are added to indicate the main priority items.



Such roadmaps provide a collective opinion about the future strategy, with agreed objectives.

As soon as the roadmap has been completed, it can be sent out to other interested parties for their additions and comments.

Roadmaps are "live" documents and should be updated on a regular basis.

7.2 Summary of Publications Relating to Energy Roadmaps

BACKGROUND TO ROADMAPPING IN THE FIELD OF MATERIALS FOR ENERGY EFFICIENCY

There are a number of roadmaps that cover both materials and energy. They tend to fall into two categories:

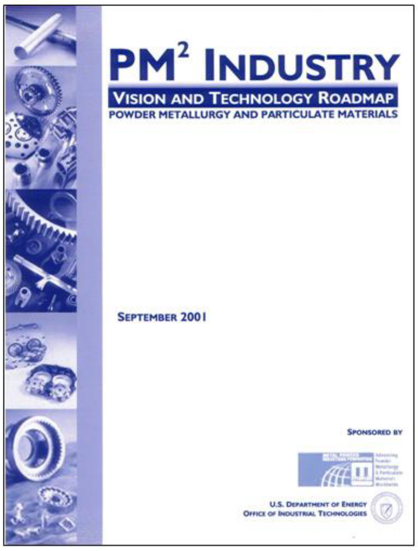
1. Roadmaps where materials are being made more energy efficiently
2. Roadmaps where materials are helping energy to be generated more easily.

The following summaries highlight the main ones:

1. Roadmaps where materials are being made more energy efficiently

POWDER METALLURGY AND PARTICULATE MATERIALS (PM^2) INDUSTRY VISION AND TECHNOLOGY ROADMAP

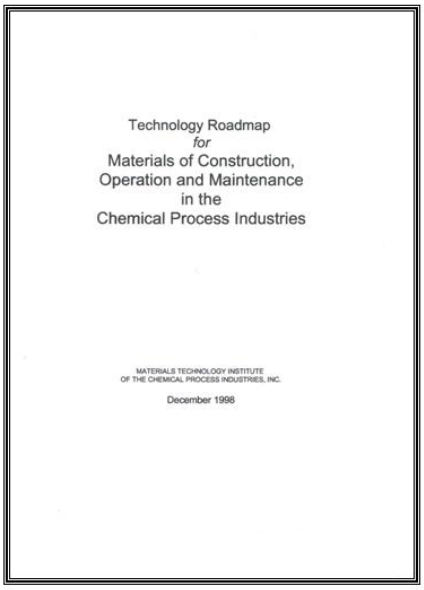
This roadmap was produced by the US Department of Energy Office for Industrial technologies and was sponsored by the Metal Powder Industries Federation (MPIF). Under Energy and Environment, one of the strategic goals is to reduce overall energy consumption by 50% by 2010 and by 80% by 2020.



Because the PM^2 process for creating components is more energy-efficient and material-efficient than competing technologies such as forging and casting, PM^2 companies will have tremendous opportunities to enter new markets.

ROADMAP FOR MATERIALS OF CONSTRUCTION, OPERATION AND MAINTENANCE IN THE CHEMICAL PROCESS INDUSTRIES

This roadmap was produced by the Materials Technology Institute of the Chemical Process Industries Inc. (http://www.chemicalvision2020.org/pdfs/matconst.pdf), as a consequence of the US Vision 2020 exercise. The objective of the roadmap, produced in December 1998, was to reduce corrosion on chemical plants and manufacture chemical much more efficiently.



The priority opportunities identified were:

- Metals with high temperature / corrosion capabilities (strong, ductile, corrosion and wear resistant)
- Materials for halogen-based processes (fluorine, chlorine)
- High temperature refractory coatings / materials
- Avoidance of fouling in heat exchangers
- Better corrosion-resistant thermal spray coatings
- Prediction of materials performance without empirical tests
- Materials that resist metal dusting
- Materials for high pressure environments (10,000 bar)
- Self-sensing systems for fitness of service.

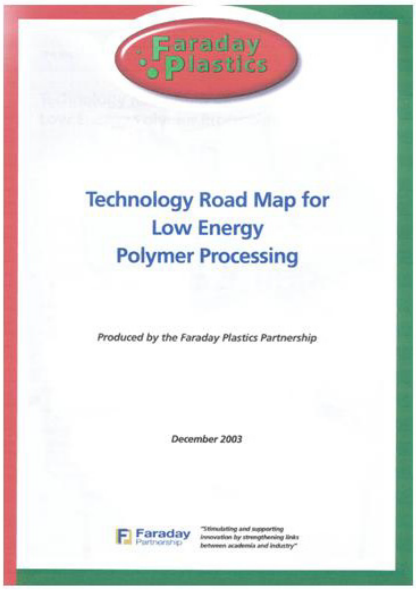
The roadmap prioritises the research needs with specific reference to new materials of construction and reduction of energy usage.

TECHNOLOGY ROADMAP FOR LOW ENERGY POLYMER PROCESSING

In December 2003, Faraday Plastics, one of the Faraday Partnerships, produced a roadmap on low energy polymer processing (http://www.faraday-plastics.com/techroadmap.htm).

Areas for research and development were identified and the main ones are listed below:

- Increased understanding of the energy balance in polymer processing
- Computer modelling of polymer processing
- Robust in-line melt temperature measurement
- Robust in-line energy measurement
- Supercritical fluid processing
- Single step processing
- Weight minimisation through micro-cellular foaming
- Fluid assisted processing.



Most of the above topics are now receiving attention, but a further 4 areas were identified as being worthy of R&D:

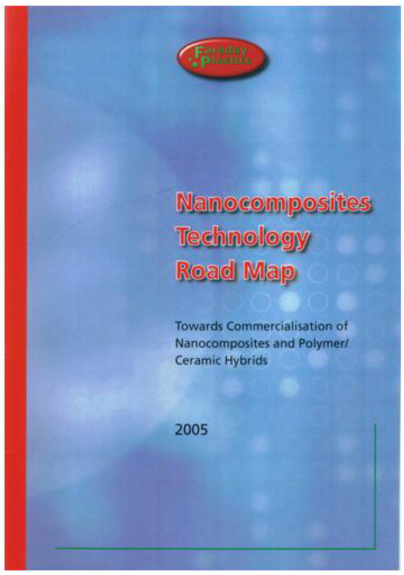
- Mixing technologies
- Process design for energy minimisation
- Intelligent processing additives
- In-line screw-wear monitoring.

This particular roadmap resulted in over £3 million funding being obtained from the EU to progress certain aspects of the findings.

2. Roadmaps where materials are helping energy to be generated more easily

TOWARDS COMMERCIALISATION OF NANOCOMPOSITES AND HYBRIDS, FARADAY PLASTICS AND HYBRIDNET

This roadmap (May 2004) focused on the developing field of nanocomposites (http://www.faraday-plastics.com/techroadmap.htm).



A summary of the likely impact of nanotechnology is given at the end of this summary.

Processing was the first main point raised by the roadmap, stating that there is a lack of understanding of how polymers filled with nanoparticles or nano-clays behave under processing conditions.

The report identified a real need to establish the processing behaviour for a range of nanocomposite materials especially when processed on traditional polymer processing equipment. Reproducibility is needed, and processing capabilities for nanocomposites should run parallel to product development and the development of reliable Quality Control techniques.

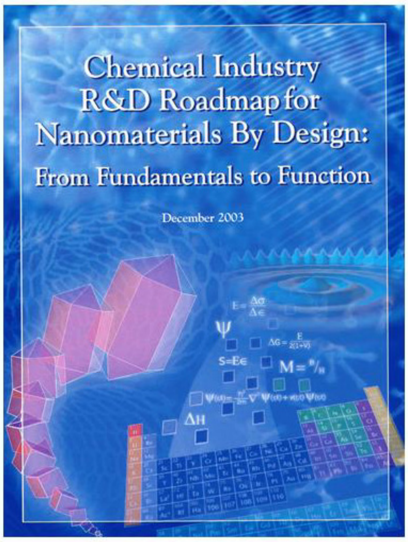
The full list of research needs for processing nanocomposites was:

- Development of processing technologies that will give reproducible products
- Develop in-line monitoring and control technologies
- Uniformity of exfoliation, dispersion and distribution on the nanoscale must be achievable

- Increased processing knowledge is required e.g. what factors affect material integrity, and how can these be controlled?
- Parallel manufacturing developments such as micromoulding need to be developed in-line with developments in nanocomposites technologies
- Presently there is a lack of knowledge of the processing characterisation of materials and how machinery design can be optimised
- Techniques must be developed that allow processing on traditional machinery
- Process induced structuring of nanomaterials must be more fully understood
- Processing technologies must be developed that are cost effective
- Quality control methods need to be developed.

CHEMICAL INDUSTRY R&D ROADMAP FOR NANOMATERIALS BY DESIGN

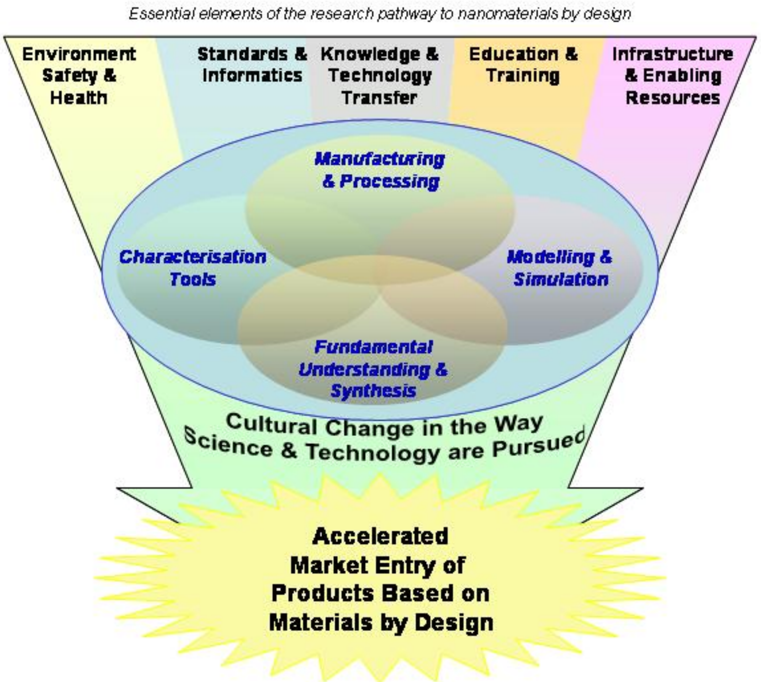
In the United States, the Chemical Industry Vision2020 Technology Partnership, in December 2003, produced their roadmap on nanomaterials. The 93 page report was called *Chemical Industry R&D Roadmap for Nanomaterials by Design: Fundamentals to Function*. It is well worth viewing at www.chemicalvision2020.org/pdfs/nano_roadmap.pdf.



It is very comprehensive; having taken a large number of people a great deal of time and effort to prepare. The emphasis is on getting nanotechnology based products to market as rapidly as possible.

The report begins by saying that Nanomaterials by Design will require concurrent development of:

- Nanoscale fundamentals and synthesis
- Methods of manufacturing
- Multi-probe measurement tools for the nanoscale
- Reliable models relating nanostructures to properties



Additional supporting activities must address:

- Environmental impacts
- Safety and health
- Standards
- Technology transfer
- Infrastructure
- Education

The report is very comprehensive, but key market opportunities for nanomaterials are specifically recorded for ‘energy’. These are listed as:

KEY MARKET OPPORTUNITIES FOR NANOMATERIALS

PRIORITY PRODUCTS / PROCESSES

ENERGY

- **Energy conversion (Gratzel [photolytic] cell type devices-dye plus nano inorganic solid polymer heterojunctions)**
- **Energy storgae (hydrogen storage, nanotubes)**
- **Batteries (high performance electrodes and electrolytes)**
- **Fuel cells**
- **Alternative energy**
- **Thermoelectrics**
- **Magnetocaloric effects**
- **Solid state lighting**
- **Supercapacitors**
- **Stronger pipes for distribution of natural gas**
- **Thermal barriers for materials enabling higher temperature combustion**
- **Materials for nuclear fusion devices**
- **Motors (higher efficiency through better magnets)**
- **High-performance catalysts**
- **Low power consumption lighting and displays**

Key material capabilities enabled by nanotechnology are given as:

KEY MARKET OPPORTUNITIES FOR NANOMATERIALS

TARGET MATERIAL CAPABILITIES ENABLED BY NANOTECHNOLOGY

ENERGY

- High selectivity, high yield catalysts that operate at low temperature
- Efficient low-cost solar cells
- High-efficiency, low-cost fuel cells and materials
- High-selectivity, high capacity sorbents
- Superior barriers with novel properties
- Novel coatings with superior properties
- Nanostructured nanoparticles and thin film coatings with quantum properties
- Electron emitting devices
- Photovoltaics and thermoelectrics
- Strong, lightweight industrial and construction materials
- Nanomaterials for net shape manufacturing of strong, ductile ceramics, metals and cements
- Sensor bearing ‘smart’ materials
- High energy density batteries and supercapacitors
- High temperature, lightweight, high-strength metals and ceramics
- Magnetic nanomaterials and devices
- Optical computing
- Optical displays

A EUROPEAN TECHNOLOGY PLATFORM FOR SUSTAINABLE CHEMISTRY – MATERIALS TECHNOLOGY – SUSCHEM

SusChem, the European Technology Platform for Sustainable Chemistry has produced (2005) a strategic research agenda, in draft form (http://www.suschem.org/media.php?mId=2678). Development priorities are listed as:

- Fundamental understanding of structure property relationships
- Computational materials science
- Development of analytical techniques
- From laboratory synthesis to large scale manufacturing.

The report looks at materials for certain sectors and novel coatings features in three. Although they are not specified as nano-coatings it is clear, from the emphasis on nanotechnology in the report, that most new coatings can be regarded as nano-based coatings.

- Energy management
  - *Self-cleaning, long-lasting coatings with high scratch resistance and weatherability.*
- Enhancement of quality for life
  - *Smart surfaces that respond to external stimuli*
- Citizen protection
  - *New functional coatings, e.g. on vehicles that reduce air resistance (or water resistance).*

The energy problem is described as shown below:

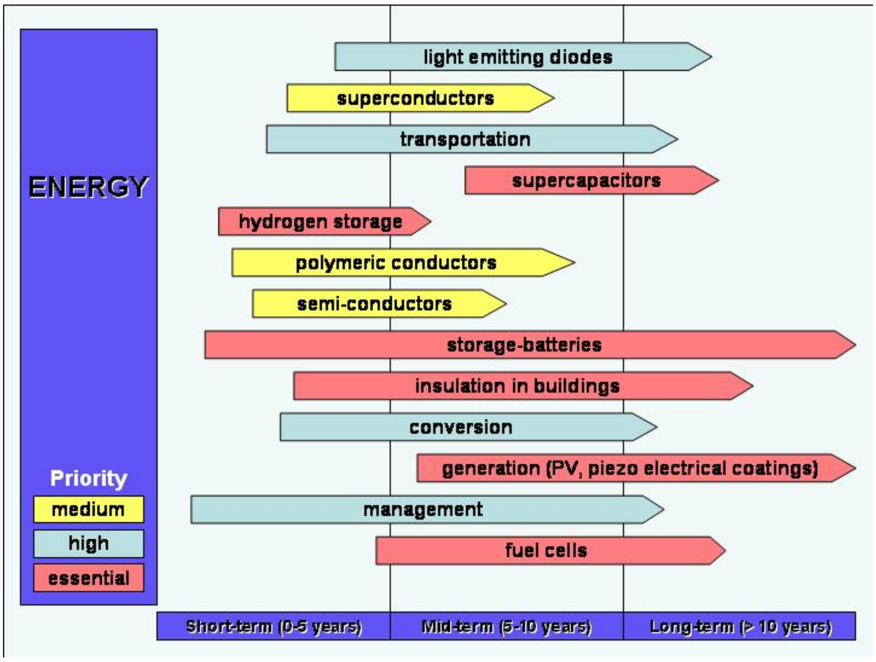
THE ENERGY PROBLEM

- **ENERGY CREATION** – **includes current technologies from fossil fuels, alternative technologies for renewable resources, such as solar, hydro, wind, geothermal, biomass for bio-refinery and nuclear. For Materials Technology, the focus is on fuel cell technology and photovoltaics.**
- **ENERGY TRANSMISSION & DISTRIBUTION** – **includes heat networks, electric wire and electric grids.**
- **ENERGY STORAGE** – **batteries, superconductors, hydrogen storage, etc.**
- **ENERGY MANAGEMENT** – **insulation in buildings, more efficient lighting, lighter materials for transport, minimisation of energy losses, etc.**

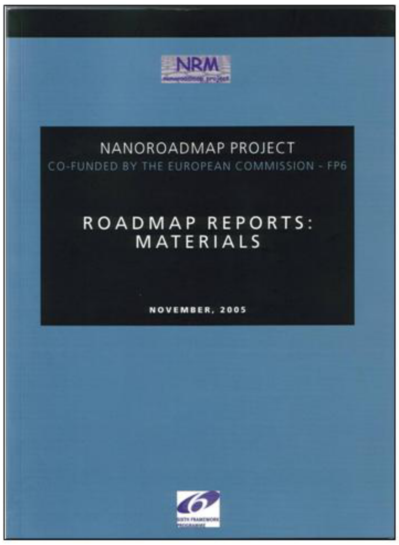
An area of considerable benefit is quoted as:

"One significant contribution to modern life would be the development of long-lasting coatings with high scratch resistance and weatherability, smart functional packaging materials, and even self-cleaning and self healing properties. Such surfaces can easily be cleaned by rain, and have a mechanism to self-repair after any surface damage."

In the section on Materials for Energy Management a 'Products Roadmap for Energy' is drawn up:



EUROPEAN COMMISSION ROADMAP MATERIALS REPORT



The Nanoroadmap Project (NRM) of the European Commission (FP6) has produced a number of roadmaps on different aspect of nanotechnology. In November 2005 they published 4 in the materials sector:

- Nanoporous Materials
- Nanoparticles / Nanocomposites
- Dendrimers
- Thin films & coatings.

They have a Delphi approach with a limited number of experts being questioned. With the publication of the four reports, they have now entered the second phase to seek input and expansion by a wider audience.

Much of the information in these reports will yield benefits for materials for energy efficiency.

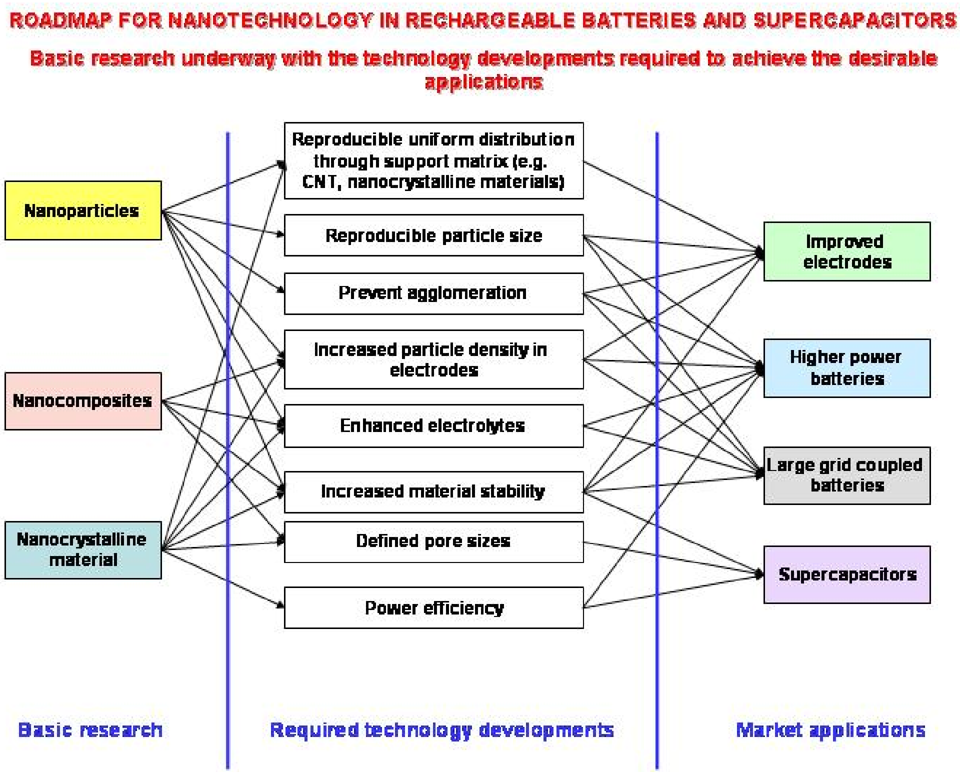
EUROPEAN COMMISSION ROADMAP ENERGY REPORT

The Nanoroadmap Project (NRM) of the European Commission has also produced four energy roadmaps in the following topics:

- Batteries and supercapacitors
- Thermoelectricity
- Solar cells
- Heat insulation / conductance.

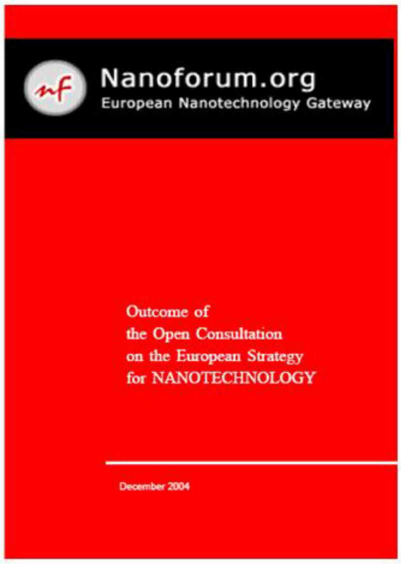
All the roadmaps completed to date, in materials, healthcare, and energy, may be accessed at http://www.nanoroadmaps.it.

For each of the Energy ones, the format is the same with a final diagram showing the basic research that is underway with the technology developments required to achieve the desirable applications. By way of example, the one for rechargeable batteries and supercapacitors is reproduced below:



EUROPEAN STRATEGY FOR NANOTECHNOLOGY

The European Nanotechnology Gateway (http://www.nanoforum.org) prepared the European Strategy for Nanotechnology and subsequently (December 2004) published the outcome of extensive open consultation with a great many groups.



Under the section on energy, the report predicts that nanotechnology will have a major impact on the following:

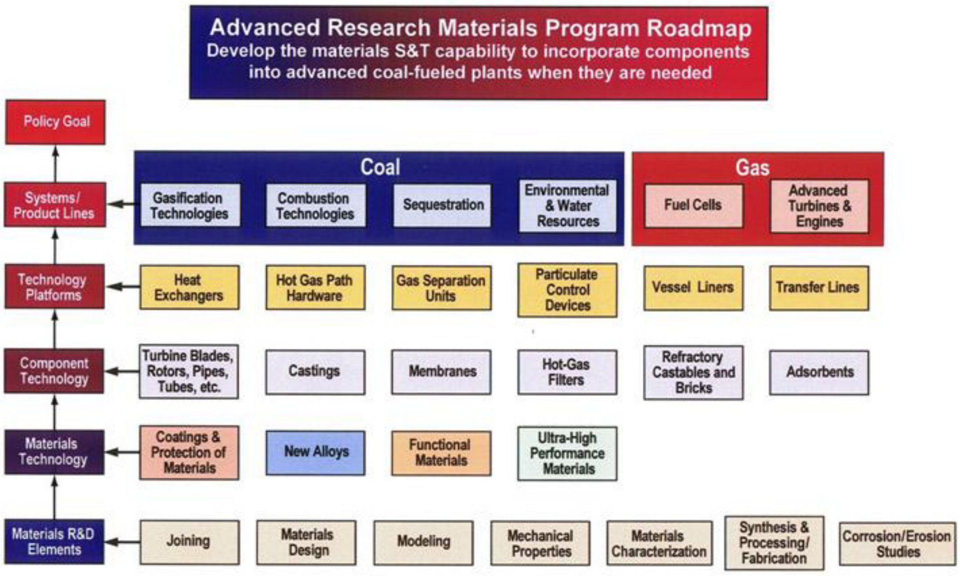
- Efficient lighting
- Fuel cells
- Batteries
- Thermo-electric sources
- Photovoltaic sources
- Hydrogen motors
- Energy storage
- Hydrogen storage.

NATIONAL ENERGY TECHNOLOGY LABORATORY – MATERIALS DEVELOPMENT

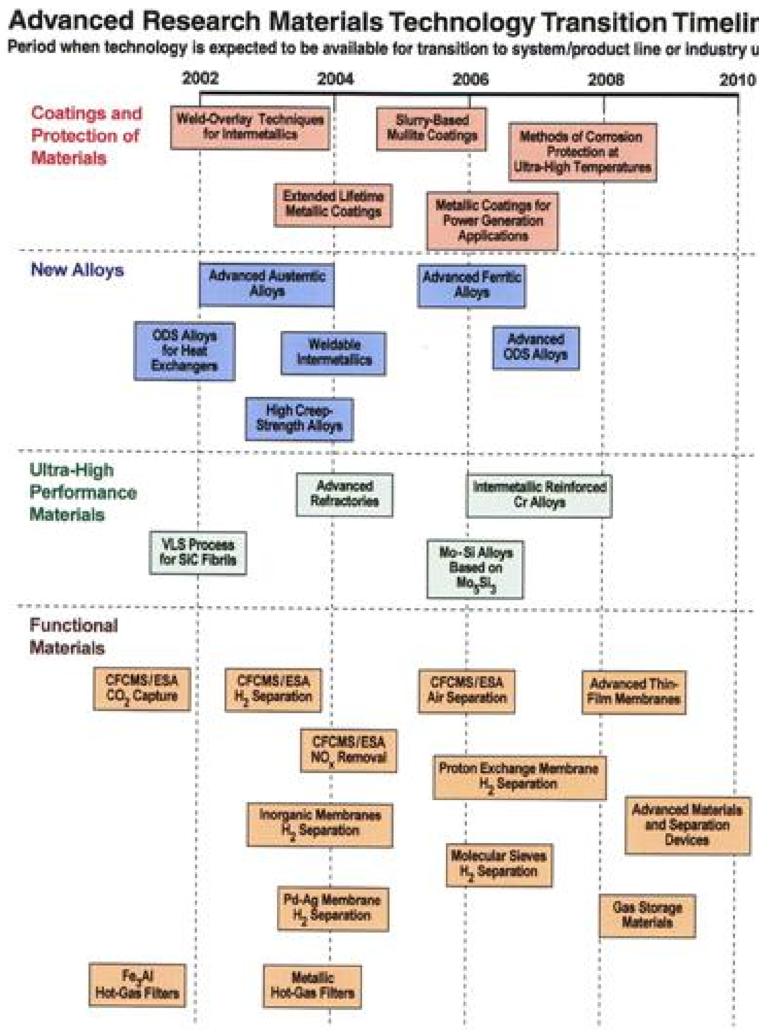
The National Energy Technology Laboratory (NETL) is the only US national laboratory devoted to fossil energy technology. In its forward-look programme it is looking at its materials needs (http://www.netl.doe.gov/technologies/coalpower/advresearch/material_pages/index.html). The focus is on:

- Structural ceramics
- New alloys and coatings
- Functional materials
- Corrosion abatement
- Vision 21
- Technology development and transfer.

There is a lot of more specific information available on the web site, but the Advanced Research Materials Program Roadmap is reproduced below:



The technology transition timelines are given as:



MATERIALS HEALTH - ELECTRIC POWER RESEARCH INSTITUTE

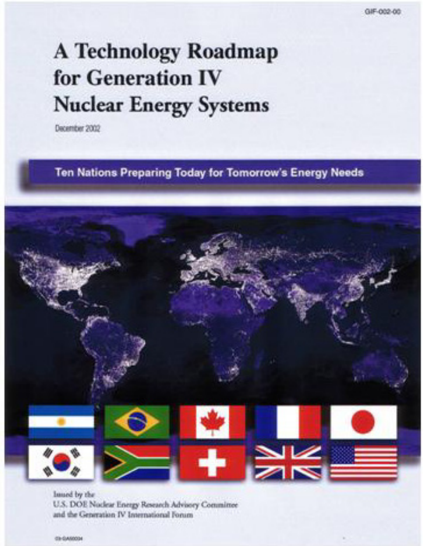
The Electric Power Research Institute (EPRI) in the States has produced a report (http://www.epri.com/targetSSTContent.asp?program=236618&value=01TSST501&objid=266790), that looks at materials use, with a view of enhancing performance and optimising reliability and lifetime for critical systems and components. Topics being assessed are:

- Condition and remaining life assessment
- Aqueous corrosion and protection
- High temperature corrosion and protection
- Advanced materials and material-related topics.

The *Electricity Technology Roadmap* that will be produced will have the following goals:

- Accelerate economic growth and productivity
- Resolve the energy / carbon conflict
- Meet the global sustainability challenge.

A TECHNOLOGY ROADMAP FOR GENERATION IV NUCLEAR ENERGY SYSTEMS



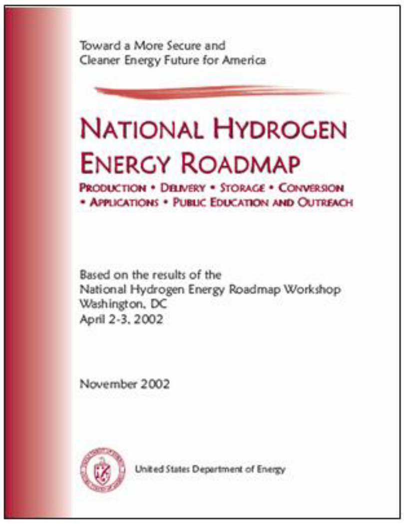
In December 2002, a roadmap was issued by the US DOE Nuclear Energy Research Advisory Committee & the Generation IV International Forum, as a result of *"ten nations preparing today for tomorrow's energy needs"*. The comprehensive report can be found at http://gif.inel.gov/roadmap/pdfs/gen_iv_roadmap.pdf.

Consideration is given to each of the Generation IV systems:

- Gas-cooled fast reactor
- Lead-cooled fast reactor
- Molten salt reactor
- Sodium-cooled fast reactor
- Supercritical water-cooled reactor
- Very high temperature reactor,

And for the most promising systems R&D is proposed. The is a section on cross-cutting fuels and materials R&D that goes into detail about the research needs for structural materials.

NATIONAL HYDROGEN ENERGY ROADMAP



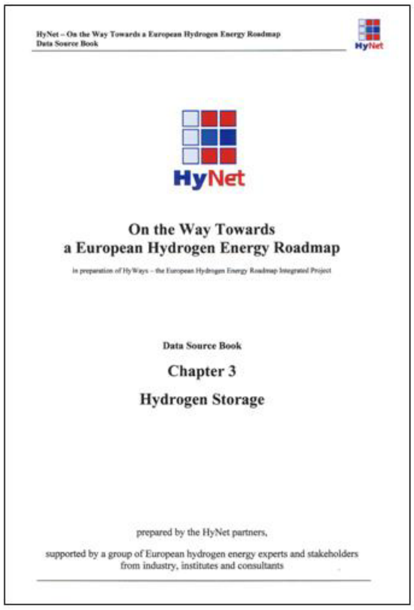
The United States Department of Energy produced a roadmap for hydrogen energy in November 2002 (http://www.hydrogen.energy.gov/pdfs/national_h2_roadmap.pdf).

The reports findings are divided into:

- Production
- Delivery
- Storage
- Conversion
- Applications,

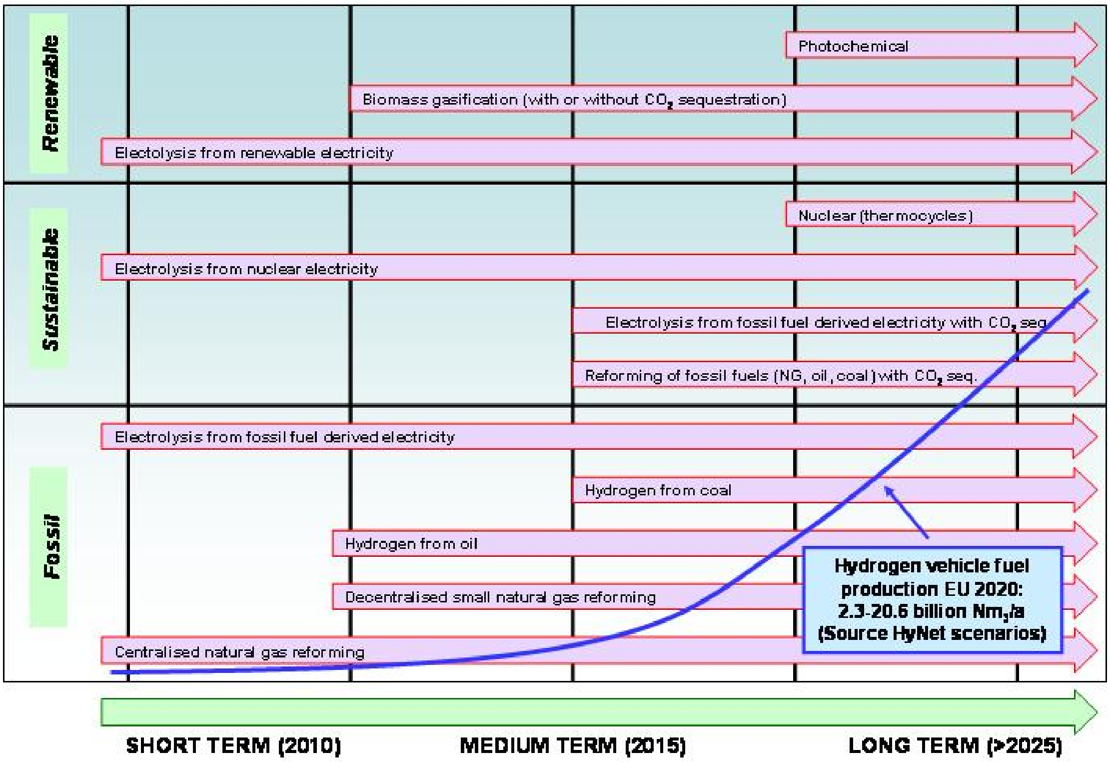
and advanced materials is a key factor in proposed R&D programmes to reduce costs and improve performance, especially in the section on storage.

ON THE WAY TOWARDS A EUROPEAN HYDROGEN ENERGY ROADMAP



HyNet have helped produce a European Hydrogen Energy Roadmap. Highlights were published in 2004, and the document is being continually updated.

The following diagram shows the timeline for hydrogen production technologies, where the arrows depict the expected earliest commercial introduction of each path.


Renewable
Sustainable
Fossil
Photochemical
Biomass gasification (with or without CO2 sequestration)
Electolysis from renewable electricity
Nuclear (thermocycles)
Electrolysis from nuclear electricity
Electrolysis from fossil fuel derived electricity with CO2 seq.
Reforming of fossil fuels (NG, oil, coal) with CO2 seq.
Electrolysis from fossil fuel derived electricity
Hydrogen from coal
Hydrogen from oil
Decentralised small natural gas reforming
Centralised natural gas reforming
Hydrogen vehicle fuel production EU 2020: 2.3-20.6 billion Nm3/a (Source HyNet scenarios)
SHORT TERM (2010)
MEDIUM TERM (2015)
LONG TERM (>2025)

Nanotechnology Developments

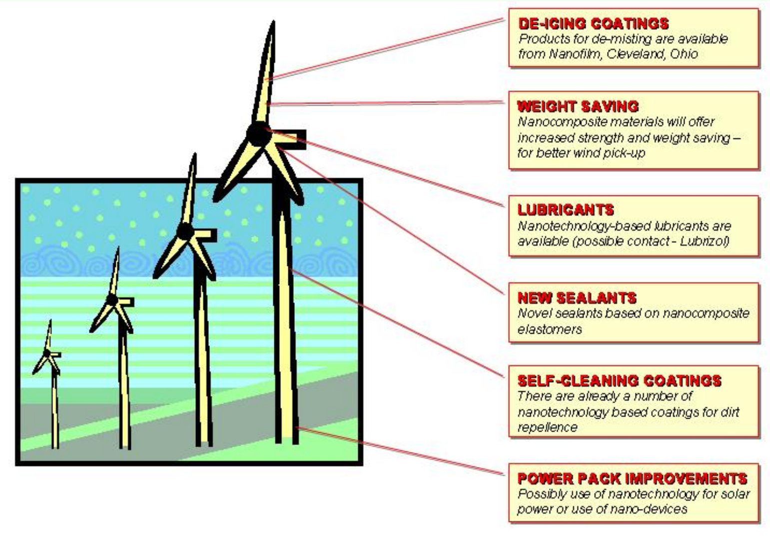
The following diagram summarises the potential of developments in nanotechnology, which are already impacting on markets:

IMPACT OF NANOTECHNOLOGY

Nanotechnology is already having a considerable effect on the automotive industry, enabling lighter weight materials and additional properties leading to new products.

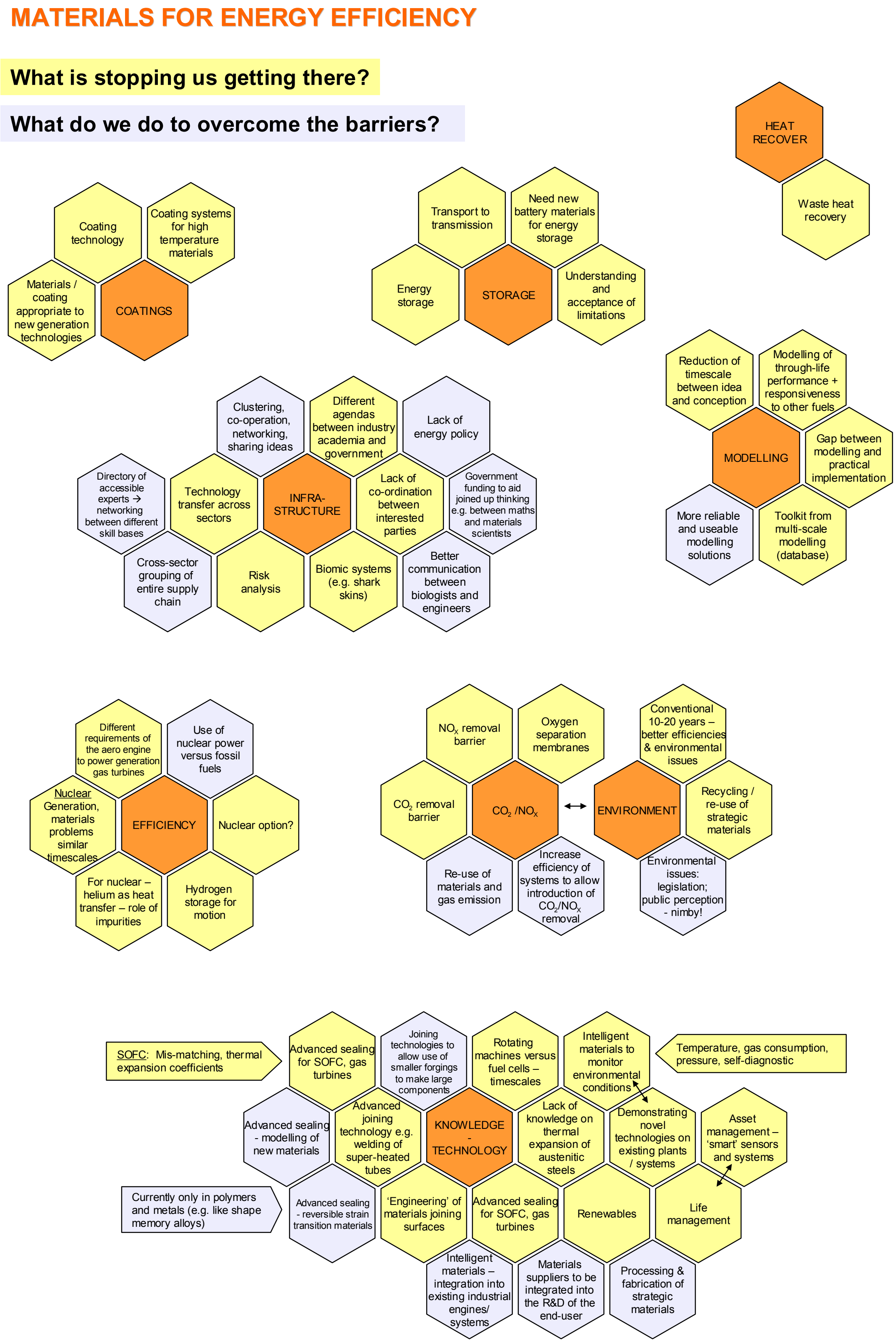
The diagram shows the possibilities, with respect to the marine sector.

Examples of use in automobiles are:



- *With 20% weight saving over conventional parts, the Toyota Camry's air intake cover and the Mitsubishi GDI models engine cover both has a nylon/nanocomposite material rather than a metal part. As well as light-weighting, this also makes use of the heat deflection properties of nanocomposite materials.*
- *The Chevrolet Impala uses 245 tonnes per annum of montmorillonite/polypropylene nanocomposite for its side body mouldings.*
- *The final lacquer on a number of Mercedes models is silica nanoparticle based and provides a durable anti-scratch surface. Other coatings developments in the field of nanotechnology are for textiles, where easy-clean coatings are now being used on Hugo Boss suits.*
- *Carbon nanotubes promise composites with 50-100 times the strength of steel and one sixth the weight! 60% of new cars in the US have plastic fuel lines incorporating carbon nanotubes to dissipate charges.*

7.3 Results of the Brainstorming with Hexagons



MATERIALS FOR SUSTAINABLE ENERGY TECHNOLOGIES

What is stopping us getting there?

What do we do to overcome the barriers?