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Future Perspectives of European Materials Research

Gerd Schumacher, Stuart Preston, Alan Smith,
Pavol Sajgalik et al.

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Specific Support Action “Foresight action for knowledge based multifunctional materials technology“ within the 6th EU Framework Programme

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Contents

Foreword from the European Commission

The specific support action “SMART” has been a very interesting project which has attempted to identify current hot spots and future trends in materials research areas over the next 5 to 15 years. The project has involved bibliometric analysis, interviewing experts from both within and outside Europe, analysing foresight studies and the organisation of three thematic workshops. These workshops were in the areas of "Materials Powering Europe", "Materials for a Safe Europe" and "Materials for a Better Life". After introductory presentations by experts in the field, the workshops' participants produced research road maps based upon the method of guided brainstorming directed by an expert moderator.

The conclusions of SMART outlined in this report support the topics that have already been chosen for the first call within the materials area of the “Nanosciences, Nanotechnologies, Materials and new Production Technologies” thematic area of Seventh Framework Programme or “FP7”. They have also been useful as input for developing future topics and strategies for European Commission-supported materials science research over the rest of the Seventh Framework Programme.

The project also underlines the importance of funding materials research for European Industry, from emerging high-tech nanostructured materials and bio- and nature-inspired materials, through industries such as automotive (2 million direct, and 10 million indirect jobs), aerospace (450,000 direct, and 1.5 million indirect jobs), chemicals and pharmaceuticals (1.9 million jobs), to sectors such as textiles, which is currently employing a total of 2 million people in Europe but which is undergoing a deep transformation by moving to high value-added products because of competition from low-cost continents such as Asia.

Europe - and indeed the world - is also undergoing major transition. The effect of society and industry upon the environment is currently a much debated theme, particularly within the context of global warming and the finite availability and distribution of non-renewable energy resources. This certainly lends great weight to the fact that some of the efforts in materials research will be directed towards areas such as renewable energy and the minimisation of industrial impact on the environment (CO_2 emissions). Issues emerging from safety and security concerns will also have an influence on the demands expected from materials research in the medium to long term. The fact that Europe has an ageing population will require appropriate research in order to cater for the longer average life expectancies of its individuals.

No-one can predict the future, even in the short-term, but the SMART project has certainly gone a long way to identifying those areas of materials research that will be important over the next 15 years.

Martyn Chamberlain
Programme Officer of SMART
Value-Added Materials Unit
DG Research
European Commission

Dear Reader

This report summarises the results of the "SMART" Specific Support Action financed within the Sixth European Framework Programme and aimed at the mapping of future materials research topics and excellent research groups located throughout Europe. Members of the SMART consortium were the Institute of Materials, Minerals and Mining (IOM3) from Great Britain, the Liten Laboratory of the French CEA, the UACH Institute of the Slovakian Academy of Science, the German Fraunhofer INT Institute (FhG-INT) and the German Project Management Jülich ("Projektträger Jülich", PtJ) at the Research Centre Jülich ("Forschungszentrum Jülich, FZJ).

It is important to recognise that in addition to the four authors named on the front cover of this report, many other experts were involved in this work: Silvia Bach (Financial Administration, PtJ), Dr. Etienne Bouyer (CEA), Dr. Anthony Flambard (PtJ), Dr. Pierre Juliet (CEA), Brian Knott (IOM3), Dr. Show-Ling Lee-Müller (PtJ), Stefan Reschke (FhG-INT), Dr. Bernd Steingrobe (FZJ), Dirk Tunger (Bibliometrics, FZJ), Dr. Birgit Weimert (FhG-INT) and many more.

In the SMART concept, forecast and foresight processes were carried out in parallel. While the analyses of published foresight studies led to identification of the three focus areas for the roadmapping workshops, in the forecast process an initial literature screening was carried out, which was followed by interviewing of experts, and workshops. Thus the information presented in this report is based on experts' opinions but it does not necessarily reflect those of the SMART members or the views of the EC. As far as possible, relevant papers have been cited and references for the sources have been given.

On behalf of the SMART partners I would like to thank all experts, (over 300 of whom were interviewed and almost 100 of whom participated in the workshops), for their strong support of this project. We would also like to thank the European Commission for their continuous support during the carrying out of this EU-funded action.

Gerd Schumacher, Project Management Jülich, Germany
Coordinator of the SMART Project

Introduction

The objective of modern materials research is to develop and tailor materials in order to obtain a desired set of properties suitable for a given application. In addition to the conventional experimental approach of trial and error, an increasing amount of essential data on materials collected by this conventional approach allows for analytical and predictive modelling and simulation. Thus, the knowledge base is continuously expanded, enhanced and refined, which facilitates more precise experimentation and the more exact simulation and tailoring of goal-orientated materials. Ultimately, this in turn results in greater over-all successes and increased opportunities for applications. The SMART project aims at providing support for establishing a sound knowledge-base for future strategic decisions concerning the strengthening of the European Research Area.

SMART is a Specific Support Action funded by the European Commission within its Sixth Framework Programme in Priority 3 “Nanotechnology and Nanosciences, Knowledge-Based Multifunctional Materials, New Production Processes and Devices”. The objective of the SMART project is to provide both the scientific community and the European Commission with important information about specific strengths and weaknesses in materials technology within the European Community as well as outline how materials research will look in the future. The aim is to create European maps of excellence in materials science and to identify the most relevant materials research topics for the next two decades by data screening, the interviewing of key experts and by roadmapping. At the core of the SMART strategy is a two-pronged concept in which both traditional forecast and innovative foresight approaches are followed (see Figure 1). The SMART process can be divided into several different stages. The first stage involved data screening on the forecast side and the identification of relevant studies on the foresight side. In the second stage, interviews of experts and the analyses of studies led to further progress. In the third and final stage, the roadmapping exercises combined in three thematic workshops both the forecast and foresight results.

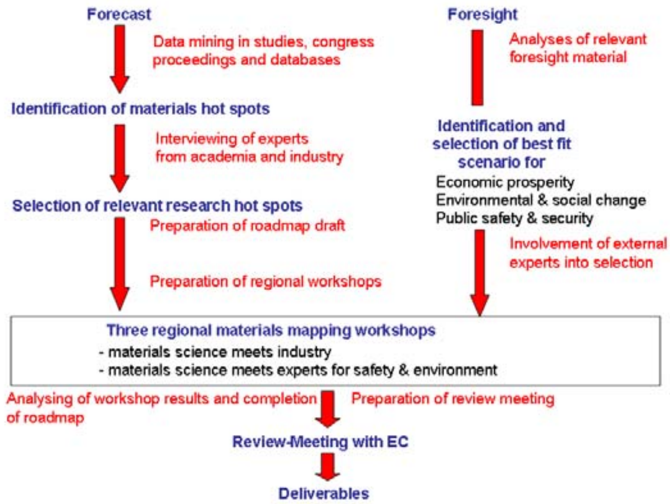

Figure 1. The SMART process

The SMART project began in April 2005 with a total budget of approximately € 480 K and a planned duration of two years. The project's Consortium consisted of five partners from four different countries. The Project Management Organisation Jülich (PtJ, Germany), a project agency mainly managing funding activities on behalf of the Federal German Ministry of Education and Research, was the Coordinator of SMART and contributed more than 20 years of materials research experience to the project. The data screening and foresight work was done by the German Fraunhofer Institute INT in Euskirchen, which has been mainly active for the German Ministry of Defence but also for other public sector clients and industry for more than 20 years. The French CEA Liten Research Institute was responsible for expert interviewing. The CEA has a wide variety of materials research activities and is one of Europe's leading research institutions in materials technology. IOM3 from the United Kingdom is one of the largest European materials societies and carried out national foresight activities for the UK Department of Trade and Industry. Their main task in SMART was the development of roadmaps. The fifth partner was the UACH Institute (Institute of Inorganic Chemistry) of the Slovakian Academy of Sciences. The Institute has an excellent overview of materials activities in Europe and especially in the new member states of the European Union. UACH was responsible for the foresight analyses.

Methodology of Roadmapping

There are a number of various methods that can be used to predict forthcoming developments and different methods aim at different time horizons[1]. Before any method can be applied, the target area has to be specified in detail. Therefore, literature screening was used to characterise the area of materials research and to define specific subgroups (see Figure 2).

Knowledge based multifunctional materials	Nano-materials	nanoparticles & -crystals
		nanocomposites
		nanofibres & -rods
		nanotubes/ fullerenes
		thin films & spintronic materials
	Smart materials	shape memory materials
		functional fluids & gels
		piezo-, ferro-, pyroelectric materials
		magneto- & electrostrictive materials
		electroactive polymers
		electro-, photo- & thermochromic materials
		tunable dielectrics
	Bio-materials	bioinspired materials
		biohybrids
		biodegradable materials
		bioinert materials
		soft matter
		bioactive materials
	Tailored Macroscale Materials for high performance applications	structural materials for extreme environments
		functional materials for extreme environments
		energy efficient materials
		electromagnetic materials
	Predictive Modelling of Materials	embedded coupled multiscale approach

Figure 2. The structure of the modern materials research area as used to define SMART search terms for bibliometrics and literature screening. The field “Biomaterials” was later changed to “Bioconceptual Materials”, which has a broader focus.

For short-term forecasts of up to 5 years, patent analyses, literature screening, portfolio analyses, quality function deployments, benchmarking and lead-user analyses can generally be applied. For the roadmapping activity in SMART, literature screening and benchmarking were used. Patent analyses could also have been used, but these were not applied since such analyses are extremely complex and would have bound almost the complete capacity of the SMART consortium.

For the mid-term forecasting range (up to 15 years), tools that can be used are expert-interviewing and expert panels, roadmapping, simulations and publication citation frequencies (also using bibliometric tools). In SMART, both expert-interviewing and roadmapping were used. The expert-interviewing was supported by a questionnaire so that statistical analyses of the results were possible. The expert-interviewing led to initial roadmapping drafts which were subsequently extended and verified at the three SMART roadmapping workshops where SWOT analysis was used[a]. The different steps in SWOT analysis are shown in Figure 3. The results of the SWOT analysis were clustered into different research areas and later converted into roadmaps.

Predictions for the long-term time horizon are extremely difficult and many experts doubt the reliability of such predictions. Methods usually used are Delphi studies and scenario methods. Many European activities in long-term predicting are summarised under the term "foresight" [b]. Foresight activities can be divided into studies (*thinkin*g the future), forums (*debating* the future) and innovation processes (*shaping* the future). The Delphi method is a very complex process and therefore not useful for small projects. In SMART, scenario methods were used by analysing existing recent foresight studies from all relevant areas such as economic studies, security studies and environmental studies. Out of the many described scenarios, those that would result in a demand for materials innovations were identified. An overview on recent foresight studies has been recently published by Verein Deutscher Ingenieure[2].

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[a] SWOT analysis, is a strategic planning tool used to evaluate the *S*trengths, *W*eaknesses, *O*pportunities, and *T*hreats involved in a project or in a business venture. It involves specifying the objective of the business venture or project and identifying the internal and external factors that are favorable and unfavorable to achieving that objective (Source: Wikipedia).

[b] A comprehensive list of European foresight actions can be found at: www.efmn.info

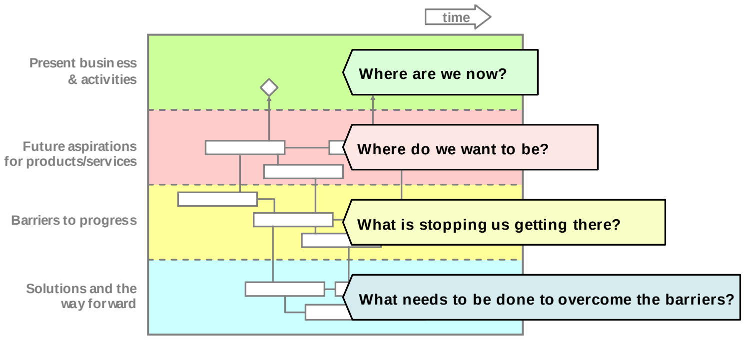

Figure 3: Stages in the roadmapping process

Figure 4: Participants clustering topics for SWOT analysis at a SMART workshop

Today's Materials Technology from a Global Perspective

Mapping and Bibliometrics

A goal of trend analysis is to decrease uncertainty and to increase factual security when attempting to predict the effects of possible changes on foreseeable future developments. At the same time, trend analysis must attain goal times efficiently and reliably. Being aware of changes and their possible timelines is a good basis for decision-making[3].

Bibliometrics involves the application of statistical methods for the investigation of publication frequency. An example is the creation of timelines and identification of "hot-spot" areas for various topics. Bibliometric analyses focus more on statistics than on real content and are generated from literature databases that do not just comprise bibliographic data but also contain information on citation frequencies and the response of other articles. The Science Citation Index from Thomson Scientific has demonstrated its suitability for the natural sciences and supplies good coverage with high precision and rapid provision of data.

Development of Materials Research

The number of scientific and technical publications has risen continuously throughout the last decades and this is also true for materials technology.

Looking a little closer at the statistics shows that whereas all types of materials research produced increases in published output, the rate of this output depended upon the research field under study. Thus, whereas the number of nanomaterials publications has tripled between 2000 and 2005, there has only been a moderate increase in the number of publications in the field of classical macroscale materials, and the relative percentage of macroscale publications has declined since the beginning of the 1990s.

It should also be noted, that some authors have also started using nano "buzz" words for classical topics during this time period, so that there has been some re-labelling of classical macroscale topics.

Two strong increases are observable in the number of worldwide publications concerning Nanomaterials: one in 1994 and one in 2000. The effect in 2000 occurred as a result of the National "Nano Initiative" initiated by President Clinton in the USA.

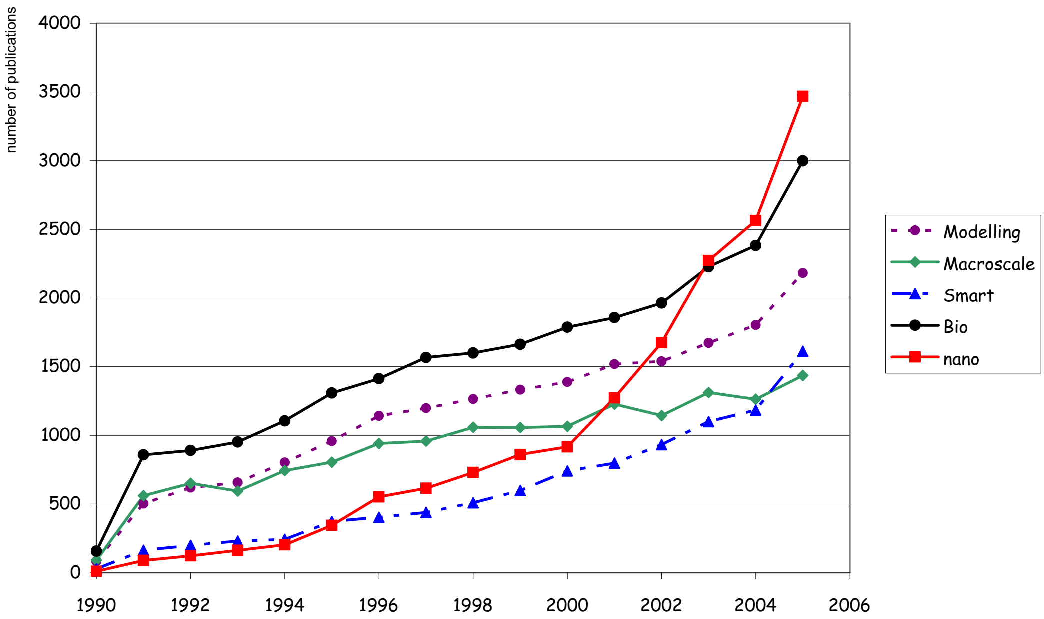

Figure 5: Development of SMART topics: number of publications

Relevance of Materials Technology for Different Industrial Sectors

Materials innovations are essential in order to produce high added value products that embed European cultural values. Industrial sectors with a high dependence on competitiveness arising from materials innovation are:

- The automotive industry
- Aerospace
- The chemical industry

- Electronics
- The textile industry
- Energy technology
- Medical technologies
- Construction
- Defence and security

The automotive industry within the European Union is responsible for a total of 3% of the GDP and for 2 million direct jobs and 10 million indirect jobs. With annual R&D investments of 20 billion €, the automotive industry is the largest R&D investor in Europe[4]. Road safety, environmental issues and passenger comfort are the main innovation drivers in this sector, which all rely on materials innovations.

More than 7000 companies are active in the European aerospace industry which employs 433,000 direct workers and which has 1.5 million indirect jobs dependent upon it. This industry invests 9 billion € into R&D annually. Milestones such as satellite systems (Galileo and GMES) and aircraft development are pushing innovation in this sector, in which materials for extreme environments, lightweight structures and electronic materials play an essential role.[5]

The chemicals and pharmaceuticals sector has 31,000 companies in Europe and employs a total staff of 1.9 million people. The chemical sector (excluding pharmaceuticals) spends 98 billion € per year for R&D.[6]. Sustainability (energy, environment, resources), flexible production processes and regulatory measures (i.e. “REACH”) are the main innovation drivers in this sector and nanotechnology and industrial biotechnology provide the means and innovation to meet these challenges. Biomaterials are the backbone of a thriving medical products industry that for example currently exceeds $50 billion in annual revenues in the United States, .

The electronics industry in Europe consists of more than 10,000 companies and 2 million employees. Drivers of long-term innovation are post silicon chip technology, energy efficiency and regulation on electronic waste and emissions[7]

More than 2 million jobs in over 120,000 companies (mainly SMEs) still characterise the European Union textile industry; an industry currently in the process of deep transformation. Innovation is a key factor in developing high value-added products which are seen as a solution to the current crisis. Today, technical textiles are already responsible for 50% of the turnover in the textile industry in some European countries and this sector is a growing very strongly in Europe as a whole.

In recent years, a growing trend to transfer textile production from the European Union to developing countries (especially in Asia) has been observed[8]. EU industry has played a leading role in the development of new products for the manufacture of textile fibres and technical textiles. The relevance of the global textile and clothing industry can be seen from the fact that textiles represent 5.7% of the production value of the world's production, 8.3% of the value of producer goods and are responsible for more than 14% of world employment. In all, the global market for textiles is worth more than 1 trillion Euros.

In the European Union, 120,000 textile and clothing companies employ more than 2 million workers and the European Union is also the largest world market for textile and clothing products. However, because of the previously mentioned trend to transfer production to developing countries special emphasis should be placed on the development of high added-value textile products (textronics), which are of special significance to the development and application of intelligent systems, intelligent clothing, textiles and footwear, as well as online systems for automatically monitoring the sewing processes of high-quality garments.

Global Mapping of Materials Research Activities

Bibliometric tools were used to obtain a benchmarking of Europe's international position in materials research. Therefore, both publication activity and publication impact (CPP) were considered. Table 1 to Table 5 give an overview of Europe's position.

Europe is competitive in all subgroups of materials science with the exception of smart materials, where its position is weak. At a region or city level, mapping showed the following regions to be ranked particularly high: Abingdon (United Kingdom), Albuquerque (USA), Ann Arbor (USA), Argonne (USA), Auckland (New Zealand), Baltimore (USA), Bangalore (India), Berkley (USA), Berlin (Germany), Cambridge (UK), Chicago (USA), Clayton (Australia), Eindhoven (The Netherlands), Evanston (USA), Halifax (Canada), Houston (USA), Jülich (Germany), Karlsruhe (Germany), La Jolla (USA), Lausanne (Switzerland), Liverpool (United Kingdom), Los Alamos (USA), Louvain (Belgium), Mainz (Germany), Medford (USA), Minneapolis (USA), Murray Hill (USA), Paris (France), Pasadena (USA), Pittsburgh (USA), Potsdam (Germany), Richland (USA), Santa Barbara (USA), Seattle (USA), Sendai (Japan), Singapore, St. Paul (USA), Troy (USA), Ufa (Russia) and Washington D.C. (USA). These results are in good comparison to the mapping of Thomson[9].

Biomaterials				
Country	**Number of articles**	**Inhabitants**	**GDP [Million $]**	**Number of articles per 10 Million inhabitants**
Japan	362	127.214.500	4.597.140	28
USA	789	290.342.600	10.450.000	27
EU-27	1287	493.000.000	11.506.369	26
China	295	1.286.975.500	1.278.900	2

Table 1. Comparison of global publication activity in the area of biomaterials (data for 2001 to 2006).

Macroscale				
Country	**Number of articles**	**Inhabitants**	**GDP [Million $]**	**Number of articles per 10 Million inhabitants**
South Korea	179	48.289.100	448.979	37
Japan	451	127.214.500	4.597.140	35
EU-27	1551	493.000.000	11.506.369	31
USA	895	290.342.600	10.450.000	31
China	434	1.286.975.500	1.278.900	3

Table 2. Comparison of global publication activity in the area of macroscale materials (data for 2001 to 2006).

Modelling				
Country	**Number of articles**	**Inhabitants**	**GDP [Million $]**	**Number of articles per 10 Million inhabitants**
USA	983	290.342.600	10.450.000	34
EU-27	1547	493.000.000	11.506.369	31
Japan	247	127.214.500	4.597.140	19
China	329	1.286.975.500	1.278.900	3

Table 3. Comparison of global publication activity in the area of modelling (data for 2001 to 2006).

Nanomaterials				
Land	**Number of articles**	**Inhabitants**	**GDP [Million $]**	**Number of articles per 10 Million inhabitants**
South Korea	333	48.289.100	448.979	69
USA	1796	290.342.600	10.450.000	62
Japan	627	127.214.500	4.597.140	49
EU-27	2302	460.000.000	11.506.369	47
Russia	273	144.526.300	312.496	19
China	1157	1.286.975.500	1.278.900	9

Table 4. Comparison of global publication activity in the area of nanomaterials (data for 2001 to 2006).

Smartmaterials				
Country	**Number of articles**	**Inhabitants**	**GDP [Million $]**	**Number of articles per 10 Million inhabitants**
Singapore	91	4.608.600	118.168	197
Japan	380	127.214.500	4.597.140	30
South Korea	137	48.289.100	448.979	28
USA	719	290.342.600	10.450.000	25
EU-27	800	493.000.000	11.506.369	16
China	453	1.286.975.500	1.278.900	4
India	81	1.049.700.200	490.630	1

Table 5. Comparison of global publication activity in the area of smart materials (data for 2001 to 2006).

Materials Research Regions in Europe

One of the most comprehensive compendiums of materials activities published is the so-called "White Book". In SMART activities and materials research excellence was identified statistically from bibliometrics, and qualitatively by conducting interviews with reputable experts. This is in contrast to the White Book which followed an approach to map activities and potentials by requesting overview articles from researchers of excellence.

Analysis of the annual number of publications (see Figure 6) in various materials research areas showed that Germany, Italy, France and the United Kingdom have high outputs of materials sciences-related publications in all research areas studied, while Poland and Spain publish significant amounts of work concerning macroscale materials. Spain has also a high output in bio-, smart and nanomaterials publications. It was noted that Sweden exhibits significant activity in modelling.

It must be noted that the above mapping examples do not contain any information about the *quality* of the research in these countries and areas. However, these results are in good comparison with the results of the global mapping for biomaterials carried out by the University of Leiden and Fraunhofer[10] in 2001.

Quality information about research can be obtained by expert interviewing. However the number of expert interviews carried out in this study was not significant enough to obtain reliable results[c].

[c] An initial analysis of high competence regions included: Bordeaux (France), Cambridge (UK), Darmstadt (Germany), Delft (The Netherlands), Dresden (Germany), Grenoble (France), Saarbrücken (Germany), Sheffield (UK), Stuttgart (Germany), Torino (Italy), Würzburg (Germany), and Zürich (Switzerland)

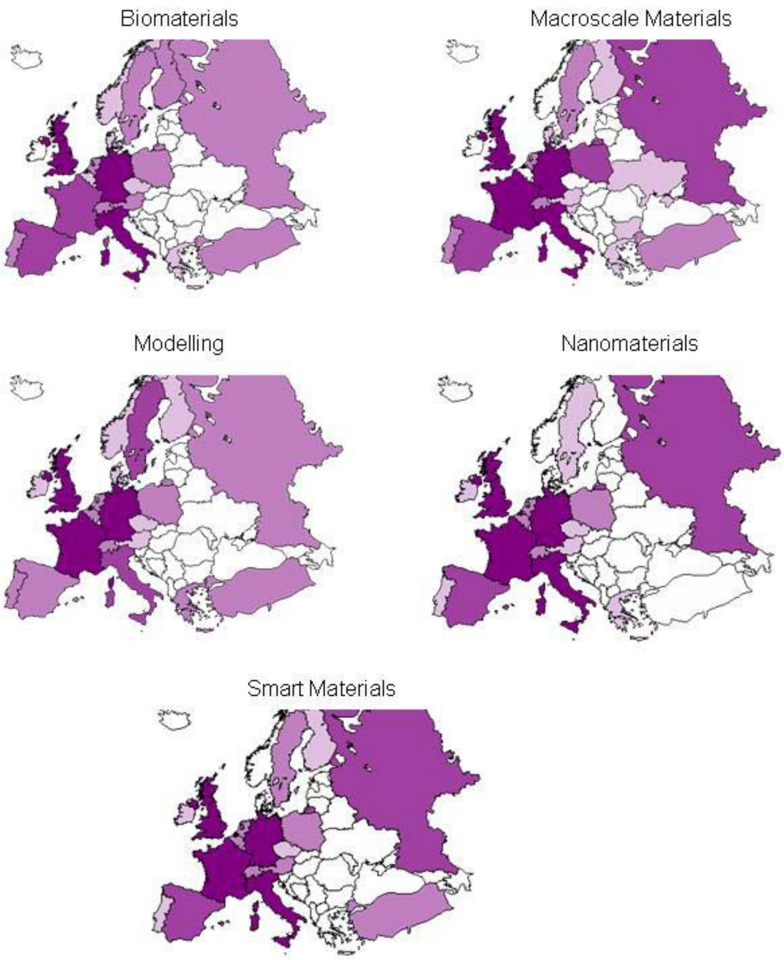

Figure 6. Mapping of materials activities in Europe

Tomorrows Materials Innovations - Looking ahead

Foresight: Materials Innovation Demands by Society

Looking into the future is a very complex matter. It is impossible to give a precise prediction of the future, but various possible scenarios for future developments can be derived. Today, globalisation is not just limited to trade, but also affects all areas of the economy and society, including research and development and the competition for skilled workers. In the late nineties most countries worldwide began to develop strategies for growth and increased standard of living, and these strategies have elements of innovation, resources, education and international marketing in common. In the USA, a national strategy was set up to meet the challenges in the globalisation of materials R&D[11]. For the European Union, the Council of Europe reacted to these developments in March of 2000 by setting up the so-called "Lisbon Strategy" which aims to make Europe the world's most competitive and dynamic economy through innovation, a "learning economy" and social and environmental renewal.

All actions in these mentioned fields rely on predicted scenarios and an important tool for predictions in the EU is the "foresight" method. Foresight[12] emerged in recent years and is a method which aims to identify innovation priorities on the bases of scenarios of future developments in science, economy and society. Since such predictions are essential for implementing the Lisbon Strategy, the Commission maintains the "Institute for Prospective Technological Studies" - one of seven Joint Research Centres of the EU which mainly strategically supports the development of EU research policies through its foresight studies. As mentioned in the chapter about methodology on page 10, scenario methods in the SMART project are used to identify long-term developments which are expected to cause materials research demands.

Therefore in the SMART study, about 30 recent foresight studies were evaluated to identify materials of interest for the next 10 - 20 years. Unfortunately, nearly one third of the foresight studies chosen were not applicable because either no potential impact of the topic towards materials innovations was identifiable or they were too general in nature. The remaining studies, both national and industrial, were investigated in detail and for this purpose a special questionnaire was developed and used by all investigators.

Priorities identified can roughly be divided into three groups of interest: *"Energy",* often in connection with environmental issues, *"Better Life",* often in connection with medicine and "*Security"*. The analyses of foresight studies showed that the scenarios would impact on all five sub-groups used in SMART: *"Nano-", "Smart", "Bio-",* and *"Tailored materials",* supported by "*Simulation"*.

The results of statistical evaluations of both general priorities and materials "hot spots" are shown in Figure 7. The column "Total" represents the total number of foresight studies investigated, while the other columns show how often the subgroups were mentioned. Since more than one priority could be mentioned in a particular foresight study, the sum of the sub-groups is not equal to that indicated by the column "Total".

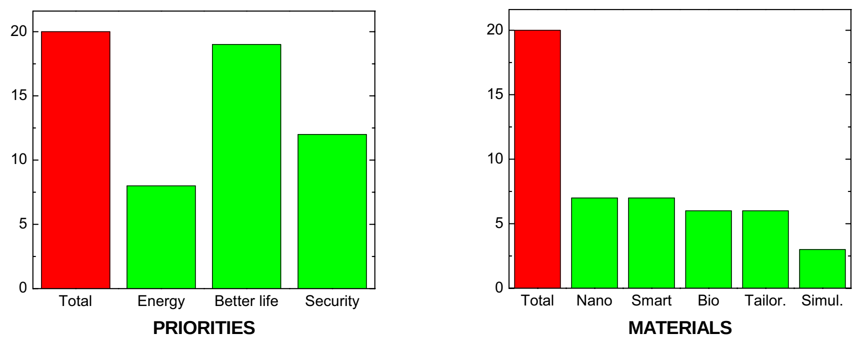

Figure 7. Distribution of foresight studies as related to *a*) political priorities and *b*) materials subgroups

It is evident that in the area of political priorities, interest in the sub-groups increases in the order: Energy < Security < Better Life (Figure 7.a) so that therefore greater interest can be anticipated in technologies which can positively modify human life (Better Life). Surprisingly, the sub-group "Energy" had the lowest frequency of appearance in the foresight studies considered, even though the problems associated with the Middle-East, where the world's largest known resources of oil are located, are well known. The "Security" sub-group has been mentioned more often than "Energy", most probably as a result of recent terrorist attacks in the USA, Europe and elsewhere.

These results suggest that some intensive foresight activities are carried out in those subject areas which are currently of high political interest. This demonstrates an inherent weakness in the foresight studies that focus on future fields from today's perspective and rely on financial funding that is given to politically biased topics, rather than focus on anti-cyclic investigations.

As has been mentioned previously, in the foresight studies several priorities for materials research were discussed which means that the combination of these priorities will be the focus of interest of European countries in the future. An example is the search for alternative energy sources with low environmental impact, which can contribute to both the "Energy" and the "Better Life" sub-groups.

A detailed view of the foresight distribution for materials in Figure 7 shows a relatively random reference to the various materials sub-groups. With the exception of "Simulation", all sub-groups have been mentioned at nearly the same level in the foresight studies. Thus, it is impossible to elucidate a materials sub-group which would play a most significant role in the future. The "Simulation" sub-group has been less frequently discussed in the foresight studies. Simulation is a highly interdisciplinary and integrative research and development tool for all sub-groups and therefore constitutes a part of each material sub-group (i.e. it is a second level sub-group). Its importance should not be underestimated, as it has been mentioned in all the more detailed foresight studies.

The priorities have also been evaluated from the viewpoint of how relevant materials innovations are for the scenarios drawn in those priority fields in which the extent of materials innovations required for certain foresight scenarios was estimated. For example in one foresight, nano-materials and smart materials were mentioned for application in "Security", while in another foresight nano-, smart and bio-materials were mentioned for the category "Better Life". This means that from these two foresights two entries were added to the priority “Security” and three entries to the sub-group “Better Life”. The numbers of all materials type relevant to the given priority sub-group were calculated in this way and the results are shown in Figure 8[d].

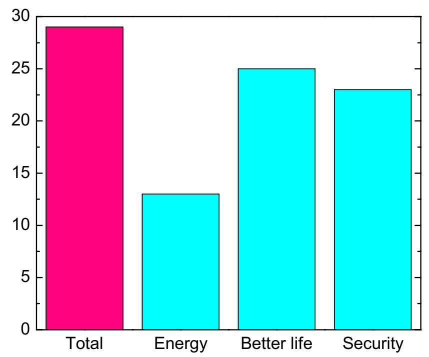

Figure 8. Relevance of materials innovations for selected foresight scenarios.

The detailed distribution of materials sub-groups in the priorities sub-groups is shown in Figure 9.

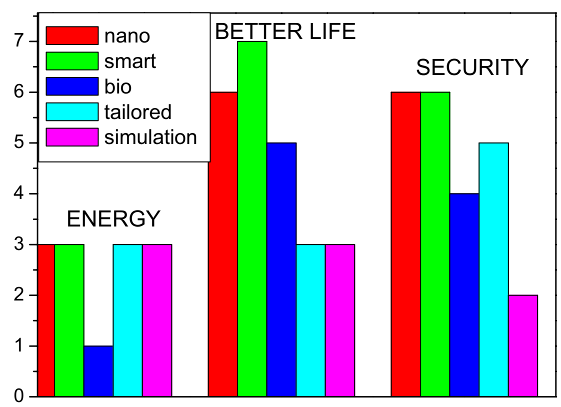

Figure 9. Comparison of foresight priorities and materials relevance, (i.e. distribution of the materials types in the priority sub-groups “Energy”, “Better Life” and “Security”).

[d] Contrary to Figure 7, here the column “Total” represents the number of all mentioned material sub-groups in the studied foresights.

The results show that substantial progress in the priority “Energy” will require developments in nano-, smart and tailored materials, together with simulation. This progress can be partially enhanced by biomaterials.

The priority “Better Life” will depend on all studied sub-groups. The main attention in future materials development for “Better Life” is expected in the field of smart, nano-, and bio-materials. Additionally, the tailored materials and simulations should further stimulate progress.

The priority “Security” shows a similar distribution of the materials sub-groups, however the tailored materials gained higher importance in this field. The leading position of nano- and smart materials is maintained. The development of new bio-materials and the application of simulations will also contribute the greater security in Europe.

The results of the foresight analyses regarding materials innovations are that ”Energy”, Better Life” and “Security” are relevant areas for shaping tomorrow’s world and that in all three areas, materials play an important role. All sub-groups of materials research should be considered.

Screening for Materials' "Hot- Spot" Areas

The forecast work covered the left-hand branch in the SMART project (see Figure 1). This is the traditional approach to predict future trends by using such methods as trend extrapolation, expert interviewing and roadmapping. Therefore the forecast process started with the data screening and was followed by expert interviewing.

In the data screening area more than 300 papers have been fully analysed. These analyses also led to the identification of keywords which were used to identify thematic hot spots and groups of excellence. Figure 10 shows the countries from where the corresponding authors originate and

Table **6** gives an overview of their research fields.

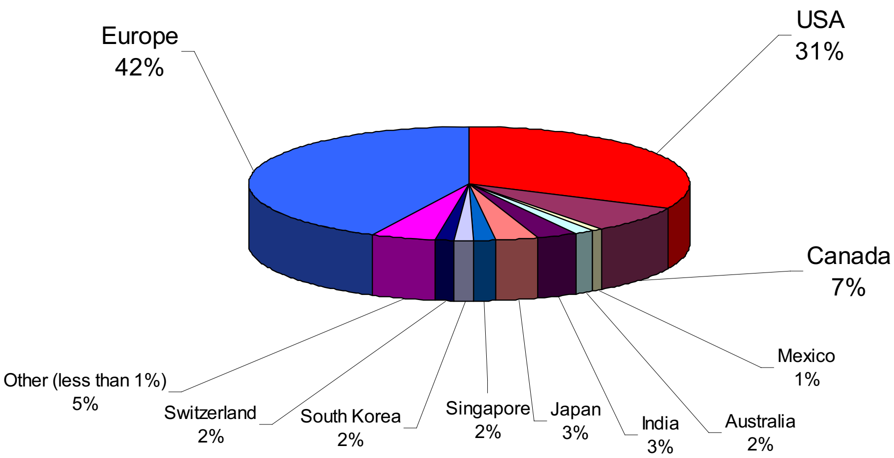

Figure 10. Data screening: distribution of the review papers according to country of the institute of the author(s).

Review-Paper Analysis Corresponding Authors Research Field	
Bio-inspired Materials	15%
Nanomaterials	24%
Tailored Macroscale Materials	25%
Smart Materials	23%
Simulation	13%

Table 6. Review-paper analysis: corresponding author(s)' research field

Analysis of the review papers led to a list of 260 materials research topics which have potential for a significant future impact on society and technology. These 260 topics were condensed by clustering to 36 different materials research fields. The analysis showed that most authors of materials science review papers expect soft matter, nanomaterials and tailored macroscale materials to be the important research topics in the near future (Figure 11). Even when the difference in the percentage of papers in the five Level 1-topics is taken into consideration, soft matter and nanomaterials still lead the statistics. In addition, the analysis showed that 50% of the 36 materials research fields belong to more than one discipline, indicating that multidisciplinary approaches will play a much more important role in the future.

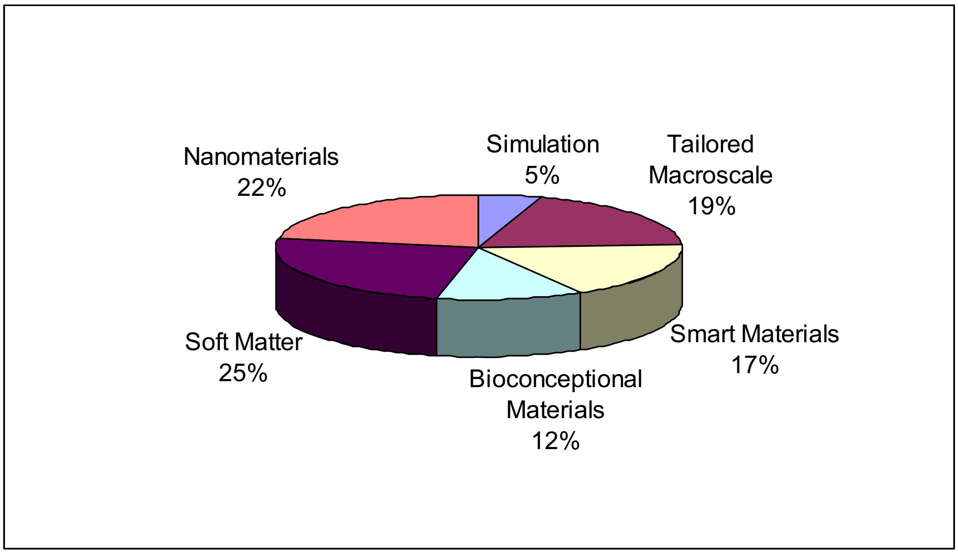

Figure 11. Relevance of materials research fields identified by review analysis. Allocation of “hot-spot” topics, mentioned in review papers as being highly relevant for the future, to Level-1 topics (multiple allocation was allowed).

Roadmaps: Materials Powering Europe

“Materials Powering Europe” was one of the three focus areas in the SMART forecast process to identify future materials research needs. All focus areas were identified through the foresight process by analysing recent foresight studies connected to social, economic and safety issues (see foresight chapter, page 22). The three roadmapping chapters are a synthesis of the three stages of the SMART forecast work combining the results of literature screening, expert interviewing and expert workshops. The focus of the workshop “Materials Powering Europe” was on energy, climate and natural resource issues. Within this category, the SMART process was open and no topics were excluded, but emphasis was mainly on *materials for energy efficiency and* CO_2 *capture* and *materials for renewable energy systems*. However before examining these two fields, some general aspects of worldwide energy trends and nuclear technology will be briefly considered.

According to the International Energy Agency (IEA), energy production and consumption will increase by 65 % in the next three decades of this century compared to the last three decades of the last century (Figure 12) with this growth in production and consumption occurring mainly in today’s developing countries (non-OECD countries). Asia is seen as the strongest growing energy market. The IEA also predicts that without policy changes, fossil fuels will remain the primary source of energy, while natural gas will grow fastest and nuclear power will drop in comparison to renewable energies (Figure 13). Since CO_2 emissions are very likely a major cause of recent climate changes, there is a growing interest in -free or reduced CO_2 technologies such as renewables, energy saving strategies and nuclear technologies.

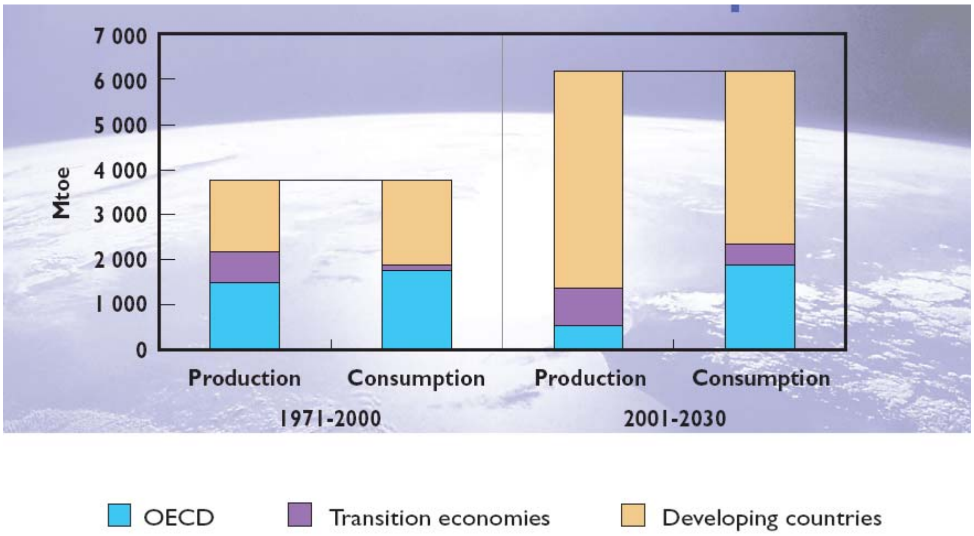

Figure 12. World Energy Outlook, Energy Trends 2005 (www.worldenergyoutlook.org)

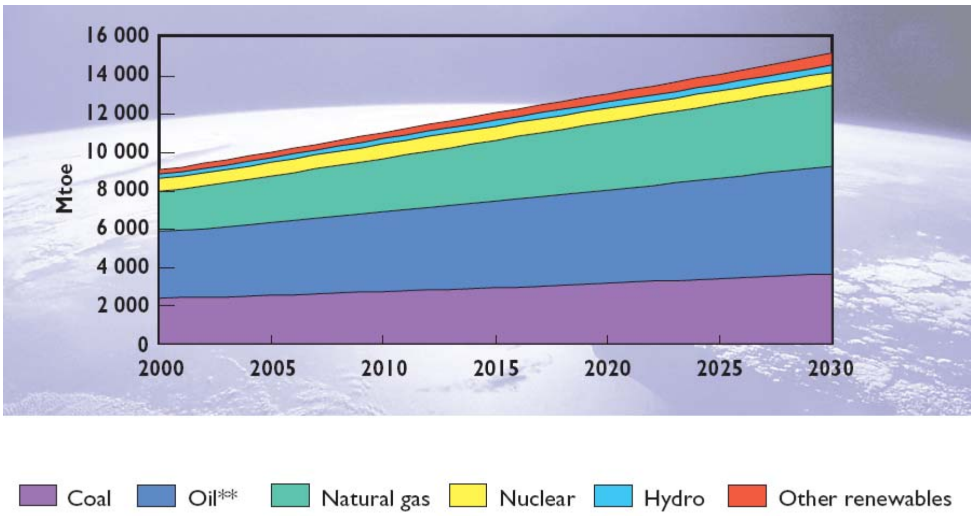

Figure 13. World Energy Outlook, Energy Trends 2005 (www.worldenergyoutlook.org)

Fission and Fusion Technologies

Today, there are more than 440 nuclear power plants in operation in 31 countries worldwide and currently (2007) there are 23 new nuclear power plants under construction with a further 39 nuclear power plants in an advanced planning stage. Despite nuclear power being a CO_2-free form of energy generation, there is a lack of social acceptance in some countries and uranium supplies constitute a bottleneck, necessitating further exploration.

Nuclear fission is a process in which a heavy atomic nucleus is forced to absorb a neutron and split into two lighter fragments. The most relevant isotopes for fission for power-generation purposes are uranium-235, plutonium-239 and uranium-233. The fission process is accompanied by an enormous energy release that is 10 million times greater than the energy released when one atom of carbon from a fossil fuel is burned. This released energy (heat) is converted into electricity via conventional steam and gas turbines. Today 66,000 tons of uranium is used per year for power generation, but only less than 1% of the uranium consists of U-235. The high market demand has caused the uranium price to rise twelve times in value since 2001[13].

A Massachusetts Institute of Technology study in 2003 “The future of nuclear power” recommends a worldwide evaluation of viable uranium resources. Furthermore, this study also states that R&D of the fuel cycle, a reduction in cost of light water reactors and the development of the high-temperature gas-cooled reactor for power generation is required. The MIT researchers also favour the so-called once-through cycle because of cost efficiency and safety, and according to their study, cost and waste criteria are likely to be those most crucial for determining nuclear power’s future.

From the technical point of view, plants in operation today are so-called ”Generation II” and “Generation III” plants. An international group of countries founded the “Generation IV International Forum”[14]. This consortium (Euratom is one of the members), aims to develop a new generation of nuclear power plant that will produce less waste, address non-proliferation issues, have lower costs of operation and an improved safety standard. The “Generation IV Roadmap” also describes the materials R&D that has to be carried out within the next years. A challenge for materials in Generation IV plants will be resistance to increased radiation damage - materials also have to exhibit long service lifetimes. Since there is a lack of available data on candidate materials, a broad testing programme has to be undertaken to set up a basis for materials selection. A bottleneck is the limited number of test facilities for the irradiation testing of materials to be used for in-core components. Also the modelling of materials behaviour is seen as a key factor in understanding the response of various alloy systems to higher temperature and radiation doses.

Besides fission technology, researchers are also developing fusion technology but this will not be ready for use for quite some time. The principle fusion process for energy production is very similar to processes that take place in our sun. There are two approaches to realise fusion on earth. Inertial fusion consists of micro explosions of small fuel pellets by means of powerful lasers or particle beams[15]. The second approach uses magnetic fields to confine the fuel. A fusion reaction that can be realised probably best on earth is the fusion between the nuclei of the hydrogen isotopes deuterium and tritium. This fusion reaction leads to the formation of a helium atom and a high energetic neutron.

In fusion, first the electrons are stripped from the atom, so that a plasma is created. Since the plasma is electrically conducting it can be confined by strong magnetic fields. When heated to temperatures around 100 million degrees, energetic collisions between the plasma ions produce fusion reactions which release high amounts of energy. Structural materials for fusion reactors are a technological barrier to the development of environmental friendly and cost-efficient fusion technology. The major challenges in the development of these structural materials are the high thermal stresses that have to be endured as a consequence of the extreme heat flux through the fusion vessel, and the degradation of the thermo-mechanical properties of the retaining materials through activation by high-energy neutrons. Currently, an international consortium is constructing the first 500-MW fusion power plant called “ITER”. Construction of ITER, which will have both demonstrative and prototype characteristics, will last at least 8 years and a service time of 15 years of the plant is expected,. Following ITER, the next step towards a cost-competitive fusion plant would be the construction of a 2000-MW fusion reactor. While it is envisaged that

ITER can be constructed with existing materials, for the next plant advanced materials will have to be developed[16,24]. A number of different materials such as ferritic martensic steels, vanadium-based alloys and fibre-reinforced composite materials currently under consideration.

Experts at the SMART workshop “Materials Powering Europe” suggested with regard to fission technology that the future hydrogen economy might depend on energy provided by nuclear power plants and therefore the necessary R&D in materials for this field has to be undertaken[24]. The experts further suggested improved communication between materials R&D engineers working in the nuclear field and those working in the area of fossil power plants. With respect to fusion technology, the experts noticed the limited number of new materials which might fulfil the requirements for advanced fusion plants. The defined goal at the SMART workshop of developing materials which will withstand 2000°C could result in some new candidate materials for an advanced costs and waste-efficient fusion technology.

Present and future developments in materials for energy will be strongly affected by the demands to reduce energy consumption, produce less CO_2 and increase energy efficiency. Although in the long-term, CO_2 capture, nuclear power plants, solar technology and (in the very far) future nuclear fusion might enable CO_2-free energy generation, diminishing resources, the growing world population and the mounting evidence of significant climate changes necessitate prompt action, since projections based on today’s energy consumption and growth rates predict a steep increase in worldwide CO_2 generation (see Figure 14).

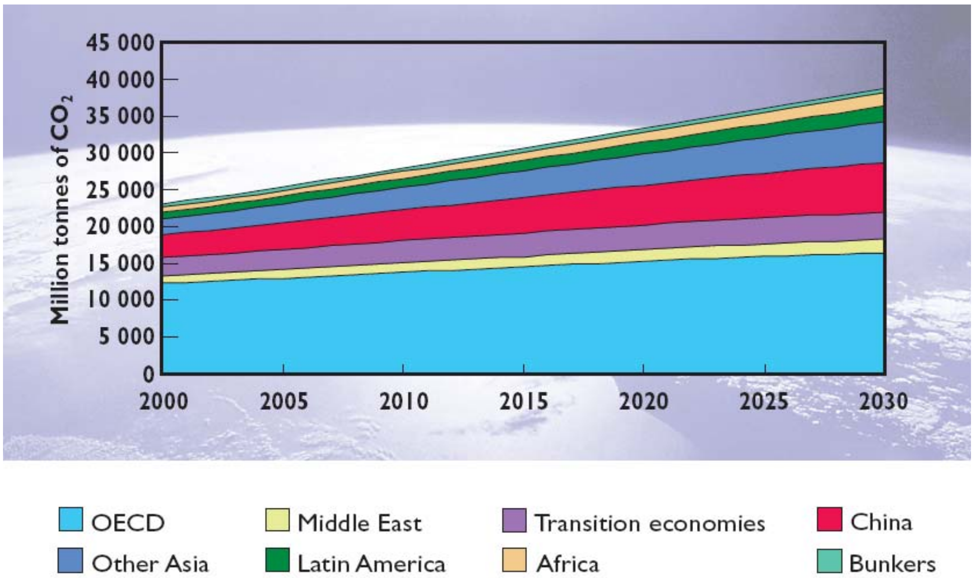

Figure 14. World Energy Outlook, Energy Trends 2005 (www.worldenergyoutlook.org)

Materials for Energy Efficiency and CO_2 Capture

Today, energy from fossil sources (oil, gas, coal) accounts for 80% of the world demand[17] and only 6.5% of the world's energy is produced from nuclear and just 0.4% from wind and solar technology. 25% of energy is produced from coal and 34% from petroleum. Therefore, even if innovation and progress towards renewable and sustainable energy technology is being made, the extremely long planning periods for conventional coal-fired power plants and their long expected service lives are good reasons to also focus on drastically improving conventional energy technology[18]. Also, alternative energy technologies have to be further developed and efficiencies have to be increased. However, associated CO_2 emissions are increasing exponentially. In 2000, there was a total coal-fired power plant capacity of more than 330 GW in the USA and in Europe, new power plants with a total capacity of 800 GW will be installed by the year 2030[19]. Also the enormous challenges facing us can be seen from the fact that every week the People's Republic of China is constructing the equivalent of two 500 MW power plants.

The CO_2 concentration in our atmosphere has now reached a value of 380 ppm which is the highest value in the last 600,000 years. It is likely that CO_2 is a major factor that affects climate change. Since it is today unpredictable how this change will affect our environment, the European Union along with many governments and the United Nations have started to take action to reduce CO_2 emissions. According to the so-called "Kyoto Protocol", the CO_2 content of the atmosphere should be stabilised and in the long-term lowered towards 280 ppm. One way to reduce CO_2 is to switch to energies that do not release CO_2. These are technologies such as wind energy, solar cells, geothermal and tidal energy, fission and fusion technology. An overview about the potentials and bottlenecks of these technologies is given in the chapter "*Materials for Sustainable Energy Technologies"* on page 52.

While a hydrogen-based economy would have many advantages over today's systems, the distribution, transport and storage of hydrogen is a critical problem. Pressurised hydrogen takes a great deal of volume compared to today's gasoline - about 30 times more volume at 100 bar for the equivalent energy content. Condensed hydrogen is 10 times denser, but is too expensive and there are safety concerns. Therefore research is currently being undertaken to find suitable materials for hydrogen storage such as carbon structures (fullerenes, nanotubes), metals and metal alloys. A promising method for hydrogen storage is the formation of hydrides by reaction with the atoms of the energy storage material. To realise high energy efficiency, the hydrogen has to be released from the storage medium with minimal energy consumption. Binding energies make it very difficult to find a medium with a sufficiently high hydrogen storage density, and easy hydrogen release. Recently, researchers have focussed attention to metal-organic framework (MOF) compounds. MOFs consist of metal oxide clusters connected by organic linkers and are a relatively new class of nano-porous material that shows promise for hydrogen storage applications because of their tuneable pore size and functionality. MOFs might even also be used for CO_2 storage, since the so- called "MOF-177" that has the highest carbon dioxide capacity of any porous material known. Lately covalent organic frameworks (COFs) have also been discovered, which have similar properties to MOF but do not contain metals. For the Hydrogen Economy, a recent workshop was held at Oak Ridge National Laboratory (USA) to develop an international strategic plan entitled “*Transforming Our Energy Future: Advancing the Role of Science and the Critical Connections with Applied Energy Programs*”.

Another technology which might be more readily attained at a large scale, is that of CO_2 capture and storage (CO_2 sequestration)[20]. This technology has been identified as a key technology for which advances in materials research are needed. This research area is labelled “*Membranes for gas separation*” in the SMART roadmap “Materials for Energy” on page 64.

There are many sources of CO_2. In addition to fossil fuel-based power generation, the cement industry, iron and steel production and converting natural gas to fuel are all sources of CO_2.

Depending upon the fuel and type of combustion processes, there are various strategies possible for CO_2 capture. In most cases, CO_2 has first to be separated from the other substances of the so-called “flue gas”[e]. This separation is necessary since most power plants utilise air for fossil fuel combustion. Thus, the flue gases from coal combustion contain only 10-15% CO_2 and the combustion product of natural gas just 5% CO_2. Storing the entire flue gas or combustion product would also mean also storing the mainly unproblematic nitrogen resulting in an inefficient utilisation of storage capacities. Therefore, the CO_2 has to be separated from the flue gas after combustion or the combustion has to be carried out in such a way that the combustion product contains virtually no nitrogen. For the former, chemical technology can be used such as by reacting the CO_2 with a solution of amines. Physical adsorption or CO_2 liquefaction are also options.

The second strategy would be combustion in pure oxygen. In this so-called “oxyfuel” process, the combustion product contains up to 80% CO_2. A challenge for the oxyfuel process is to provide the necessary oxygen by separating it from the rest of the air. The oxygen could be liquefied or membranes could be used for selective extraction or materials could be used that adsorb nitrogen. These challenges for materials research have been identified as a key issue for future materials research in the roadmap on page 64. Experts[18,21] also state that oxyfuel processes change the entire

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[e] A combustion product which goes up the smokestack; the other major component is nitrogen which does not participate in the combustion process

combustion process and are calling for research on the corrosion of advanced materials in such power plants.

Finally, a third strategy could in some cases be to remove the carbon from the fuel beforehand and, for example, just combust hydrogen.

Following separation the CO_2 has to be stored and the options open for this have been analysed by the German Physical Society. In principle, storage is possible in oil and gas reservoirs, mine cavities and in saline aquifers or in the ocean / deep sea. The storage in geological formations of porous and permeable sandstones such as empty oil and gas reservoirs would be an opportunity for long-term CO_2 storage.. The storage capacity in such formations is relatively low, as with mine cavities. There is an almost unlimited storage capacity in the oceans and the deep sea, although experts warn that the environmental effects of dissolving CO_2 into seawater cannot be predicted and that therefore ocean storage is too unsafe. Deep sea storage at depths beyond which CO_2 is denser than the seawater would be another option but this technology would be extremely expensive. Saline aquifers also have a significant storage capacity for CO_2 which has been estimated at several 1000 Gt worldwide and storage in such aquifers would only increase the price of 1 kWh by 5 cents. Even if CO_2 production would increase exponentially, this storage would probably last for several decades. A risk of this technology, however, would be an undiscovered leakage or a sudden major gas release.

The Energy Working Group of the Asia Pacific Economic Cooperation (APEC) is carrying out a large three-phase project to explore CO_2-storage capacities in the APEC region (which includes the USA, Canada, Australia, Russian Federation, People's Republic of China, Mexico and Peru)[22] and to evaluate the technological requirements for CO_2 sequestration. Two case studies are taking place at the moment: The "Saline Aquifer CO_2 Storage Project" is being carried out by Statoil in the Norwegian North Sea and a second project is taking place in Weyburn, Saskatchewan (Canada). In Germany the first CO_2-free 30 MW coal-fired power plant is being constructed by Vattenfall at Schwarze Pumpe[23] in Brandenburg State. BP oil company are also building the first large-scale plant for the production of CO_2-free electricity in Scotland. The BP plant will transform natural gas into hydrogen and CO_2

and the hydrogen will be used to operate a 350 MW power generator. The latest developments in CO_2-capture technology can be found at the website of the FP6 project ENCAP (www.encapco2.org).

Even though many experts expect that CO_2 capture and storage has the greatest potential to avoid a further increase of CO_2 emissions, it is still unclear if an up-scaling of this technology to a global scale will be possible from a political, technical and economic point of view. At the same time, it is certain that fossil energy resources are limited, so attempts to use energy more efficiently are of high importance. A significant reduction in CO_2 production could be realised by savings in energy consumption and some of these savings are also connected to materials research demands such as the development of energy-saving LED lighting (organic electronic materials)[24]. The world market for LEDs is currently estimated at 6 billion € with an annual production of 50 billion units. Already half of this production are high-brightness LEDs for lighting applications such as automotive tail lights, stop lights and large displays[25].

The construction of light-weight structures is another application area for energy savings. Energy savings are very important in the mobility sector and since today there are more than 600 million cars and trucks worldwide. For air and land transport, light-weight concepts are already being applied by employing light-weight materials such as foams, Al or Mg-based alloys and composites (bio-composites[26]) and by designing smart structures for conventional materials (such as steels) which contain less material yet exhibit the same or an even better performance. Nanomaterials such as nano-composites have widened the opportunities for the engineering of light-weight structures. In addition nanomaterials can reduce friction in moving parts and therefore increase energy efficiency[27]. Further approaches for energy saving can be derived through smart materials concepts, and phase-change materials could be used for climate control in housing, for example[28].

Figure 15. Lightweight materials. (Simple engineering with today's available innovations allowed Loremo to construct a car with a fuel consumption of only 1.5 litres of fuel per 100 kilometres[29]. It is powered by a 2 cylinder turbo diesel engine.)

Energy Transmission

Figure 16. Energy losses in power transmission are about 8 to 10%.

The European vision for a future electricity transmission network can be found in the Strategic Research Agenda of the European Technology Platform "SmartGrids"[30]. Future networks should be highly flexible, fulfilling customer needs with highly efficient power generation and low or zero CO_2 emissions, and be reliable and economic. Materials play a great role in the development of future power cables and there are a number of issues currently being investigated, including the development of fluid and gas-filled cables. Another key factor is the intrinsic conductivity of some polymers, which could lead to the development of polymer dc-power cables that are produced through a simple triple extrusion process[31].

In the future, many experts expect enhanced transmission will be carried out by superconducting cables. In the search for practical applications for the superconducting effect (discovered 1911), in 1986 it appeared that a breakthrough was very close when Bednorz and Müller discovered superconducting high-temperature copper oxide in a Swiss research lab. In the late 1980s and early 1990s, much research was carried out to find even better materials, but finally it turned out that it was not the materials themselves but their processing which was making potential applications expensive. Important progress in superconductor research was nevertheless made in 2001 by two Japanese researchers who found superconducting intermetallic magnesium diboride[32] (transition temperature: -234°C).

At the same time, progress was made in developing highly efficient cooling systems that do not require the use of helium. Superconductors already have a variety of applications and by reducing their cost, more promising applications might be realised in the future. Today, the biggest market for superconductors is in high-performance sensors required for magnetic resonance imaging (MRI). Potential future applications include high and low-temperature superconducting (HTS and LTS, respectively) power cables with ultra low AC losses, transformers (oil-free and increased efficiency), motors, current limiters, and SQUIDs[f] for measuring brain waves and for enhanced devices in radio communication[33]. Recently Nexans and RWE reported that they have successfully tested a current limiter in a 10 kV grid[34]. Also, superconductors could reduce the weight of generators in wind turbines by 30% (up to 150 tons).

Power lines consisting of nanotubes as has been announced by US National Nanotechnology Initiative, do not appear viable from today's viewpoint of scientific knowledge[35]. There might be contactless energy transmission in the future through microwave transport via orbital satellites, but it is very likely that most energy will be transported as electricity along transmission cables[36]. The most significant changes in the future might be seen through changes in the energy grid itself and it can be expected that in the future most consumers will also be energy producers and will have their own local energy storage systems. A transition to smart, resilient, distributed energy systems, coupled with pollution-free energy carriers, e.g. hydrogen and electricity, can be expected[37].

[f] Superconducting Quantum Interference Devices; sensor to measure extremely small changes in magnetic fields.

Increasing Energy Efficiency

There are several sectors where increasing energy efficiency is of strategic importance. These are dominated by power generation but energy efficiency is equally important in the construction sector (especially the built environment), steel production and electrical energy storage.

Increasing Efficiency of Power Generation

The highest energy savings could be realised at the source itself, by increasing the efficiency of power generation and combustion processes. Currently, the highest efficiency of coal-fired energy generators is 55%, and further improvements in the efficiency of gas turbines and boilers are needed. In the section "Materials for Energy Efficiency" in the roadmap on page 64 materials developments required to make energy generation more efficient have been identified.

Modern gas turbines require a significant increase in gas inlet temperatures in order to obtain maximum efficiency[38]. Therefore enhancements in the service temperature and the corrosion resistance of the blade material are needed. In general, corrosion and environmental degradation are thermally activated processes with an expected increase in severity as the temperature increases. In power generation, an industry currently dominated by the use of fossil fuels, fuel flexibility is now a coveted goal and the use of coal and synthetic gas can lead to potential hot corrosion issues.

The blades in modern aero, marine and industrial gas turbines are manufactured exclusively from nickel-based super alloys. Developments in materials for gas turbine blades are moving towards ceramics, reinforced aluminides and silicide-based components[39], although completely new materials systems (not materials) will be required by the year 2020. As the nickel-based super alloys are actually operating above their melting points in many cases, improvements in thermal barrier coatings (TBCs), ceramic coatings that protect the metallic blades from the high temperature and hot corrosion attack, are essential. The nickel-based super alloys are first coated with a hot corrosion-resistant MCrAlY-bond coating which also provides the rough surface required for the TBCs which are layered on top of the MCrAlYs. For the development of these materials, new techniques for measuring the mechanical properties of coatings are needed[40] and higher temperature ceramic systems (>1400°C) especially for industrial gas turbines have to be developed, as well as better bond coatings[41]. Current technologies used to deposit the coatings are electron beam physical vapour deposition (EBPVD) for aircraft engines, and plasma spraying for power generation turbines. Both are line of sight techniques so parts of complex geometry cannot be readily, if at all, adequately coated all over. The usual material for TBCs is yttria-stabilised zirconia (YSZ). Their failure mechanisms, non-destructive evaluation, life prediction and life remaining assessment will continue to be active research topics. Also, technologies will need to be developed which will improve coverage and reduce thermal conductivity, since all TBCs sinter in service progressively reducing porosity and increasing thermal conductivity (the porosity normally provides the insulation).

Since gas turbine technology is a very safety-sensitive field in aircraft applications, and because long lifetime requirements are critical for energy plant applications, the modelling of materials for improved coatings and life prediction is a key factor for gas turbine development.

For the future, advanced combustion plant boiler and steam turbine materials have to be developed which will have to face conditions of temperatures above 700°C and pressures at 350bar; these will be required by 2015. Austenitic steels for high temperatures are needed, which will progressively replace Cr steels. Currently, there are solutions for up to 600°C [42] and since predictions are often based on trial and error, in general a better understanding of microstructures in such materials is needed.

Energy Efficiency in Construction

Huge amounts of energy are required for heating, cooling and lighting buildings, often in an unsustainable manner from fossil fuels. Such uses account for around 42% of all the energy consumed in Europe, whereas construction activities account for about

5% of the energy used. For this reason, the energy consumptions of urban areas and of buildings in particular, must be dramatically reduced.

The first requirement is to develop a new generation of “highly efficient buildings”, with reduced energy demands. But the existing stock has long life-times and solutions to retrofit existing buildings are lacking. In today’s context, 80% of energy consumed during the whole life-cycle of a building is consumed during its service life (and only 20% for materials, construction and demolition). Reduced energy consumption must therefore be examined for both new and existing buildings, yet both areas need different R&D programmes. Energy-efficient buildings require new concepts whilst new technologies are necessary for retrofitting existing buildings to significantly reduce current energy consumption. In the medium term, this will require embedded renewable energy sources, cladding and ventilation technologies, sensors and pervasive computing systems to develop the concept of the “Intelligent Building”. In the longer term, buildings will need to be developed as an active part of the entire energy system.

Similarly, there is a requirement for efficient and environmentally friendly construction materials. For example, innovative materials and technologies for the recycling / reuse of construction waste, and reduced raw material demands combined with integrated life-cycle processes for flexible buildings and infrastructures.

Energy Efficiency in the Steel Sector

Almost all European manufacturing sectors are largely based on the utilisation of steel in various forms and these are dominated by the construction and automotive sectors. The construction sector has been discussed above. The automotive sector has to address environmental sustainability with respect to energy consumption, CO_2 emissions, resource efficiency and dismantling and recycling behaviour such as the EU “End of Life Vehicle” directive.

Electricity and natural gas supplies make up a significant part of steel production costs although energy consumption and CO_2 generation in the European steel industry have decreased by 50% and 60%, respectively, over the past 40 years.

Since the beginning of the 1990s, blast furnace processes have approached their physical upper limits with respect to energy efficiency. A sustainable approach towards by-products and residues is also a must. Three major themes have been identified: the greenhouse gas challenge, energy effectiveness and resources savings and the social impact of materials.

Certain research areas have been identified that will be required to enable a safe, clean, cost-effective and energy-efficient steel production. These include the development of sensors, robotics and process modelling.

Efficiency in Electrical Energy Storage

Both fuel cell and hydrogen storage technologies have already been identified on the roadmap as medium-term requirements for energy storage (see the following section on the hydrogen economy). Another important area is the development of materials for batteries often for medium-power applications including integration with fuel cells.

An important criterion for the choice of battery material is the relationship between specific energy and energy density. The old lead-acid battery is at the bottom of the scale (and is large in size) with Zn-air and Li-air batteries at the top of the scale (and small in size). Future considerations will look at multifunctional materials and systems. Where weight is an important factor, as in electric-propelled unmanned air vehicles (UAVs), polymer lithium-ion cells are being developed and refined to form part of the overall storage system. These light-weight batteries may also be considered for automotive applications and would be particularly attractive when combined with renewable energy sources, such as wind turbines, for re-charging.

The Hydrogen Economy

Fuel cells are being developed for use in mobile applications, in stationary applications and to power portable devices such as notebooks[43]. The fuel cell is an electrochemical power generator and its principle has been known for over 150 years.

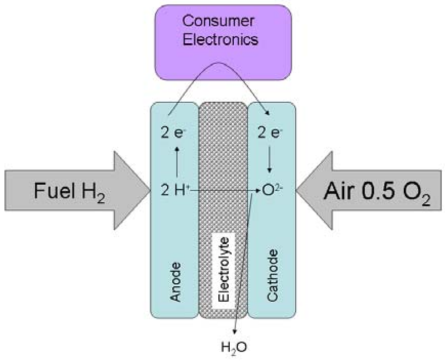

Figure 17. Principle of the fuel cell.

There are a variety of fuel cells which differ in working pressure, working temperature, employed fuels and electrolytes. A common principle of all fuel cells is that two electrodes are separated by an electrolyte as shown in Figure 17. One of the electrodes, the anode, is supplied with hydrogen or a hydrogen-rich gas, and forms positively charged hydrogen ions. The other electrode, the cathode, produces negative oxygen ions from oxygen or an oxygen-rich gas. The result is an electric voltage between the electrodes which can be used in practice by linking both electrodes via an external circuit through which electrons flow and generate work, whilst the movement of ions in the electrolyte produces charge transport within the cell. The theoretical cell voltage under standard conditions is calculated to be 1.23 V, whereas in practice, technical cells will achieve cell voltages oscillating between 0.6 and 0.9 V). To achieve higher voltages multiple cells are connected in series.

Five fuel cell types have been developed commercially. These are the alkaline fuel cell (AFC), polymer electrolyte membrane fuel cell (PEMFC), phosphoric acid fuel cell (PAFC), molten carbonate fuel cell (MCFC) and the solid oxide fuel cell (SOFC). These fuel cells can be categorised according to their working temperature into low, medium and high-temperature fuel cells.

Alkaline fuel cells, polymer electrolyte membrane fuel cells and direct methanol fuel cells belong to the low-temperature fuel cells which means that they operate at about 80°C. AFCs are operated with potassium hydroxide solution as electrolyte. All materials problems associated with AFCs are considered to be solved, but because of their sensitivity to CO_2 and CO, most companies and research institutes have stopped developing this fuel-cell type.

Similarly to AFCs, even small amounts of CO can damage the catalysts in PEMFCs so that the carbon monoxide produced together with hydrogen during reforming has to be reduced to a content of about 10 ppm. The electrolyte used in this type of fuel cell is a thin, gas-tight, proton-conducting plastic membrane. The water necessary for ion conduction in the currently available perfluorinated polymer membrane limits its possible working temperature and the strongly acidic character of the membrane makes it necessary to use precious metal catalysts. PEMFCs have reached a high degree of technical maturity.

The DMFC is an improved version of the PEMFC, where again the electrolyte is plastic. The great advantage of the DMFC is that the anode can be supplied with methanol whilst the cathode can be supplied with air so that the methanol does not first have to be converted into hydrogen in a reformer. Further research is needed on the precious metal catalysts involved and to improve the reliability of the membranes used. The DMFC is still in the development stage and some research bottlenecks such as diffusion limitations and intermediate products blocking the surfaces of the catalysts have yet to be solved.

The PAFC is an intermediate-temperature fuel cell that is operated at 200°C and supplied with hydrogen fuel usually reformed from natural gas and air. It operates with an electrolyte of nearly water-free phosphoric acid gel. The advantage of the PAFC is its high tolerance towards CO_2. Even though this fuel cell type has a low efficiency, it is a cell type that is commercially available and installations from 200 kW to 11 MW have been already made. However the profitability of this fuel-cell type still needs improvement.

The molten carbonate fuel cell (MCFC) working at about 650°C and the solid oxide fuel cell (SOFC) operating at 1000°C are both high-temperature fuel cells. MCFCs have the carbonates Li_2CO_3 and K_2CO_3 as electrolytes which are fixed in a porous ceramic matrix. Carbonate ions play a key role in the MCFC concept and since CO_2 is part of the carbonate cycle in MCFCs, this fuel cell-type is very advantageous in converting carbon fuels into electricity by using the so–called “internal reforming process”. This is driven by waste heat of the stack and converts the fuel to hydrogen and CO_2. Therefore MCFCs are able to directly process natural gas, biogas and coal gas. This fuel-cell type is constructed from very affordable materials such as steel, ceramics (which carry the electrolyte) and nickel / nickel oxide (electrodes). However, there are still strong demands for materials research since the molten carbonates create a highly corrosive environment. This is a key issue since the short lifetime of this cell type and cost-consuming maintenance work are barriers for a broader use of MCFCs. Currently, the first MCFC pilot power plants are operating at the range of 2 MW.

The high operating temperatures of SOFC are causing a variety of problems. SOFC have a gas-tight ceramic electrolyte (yttrium-stabilised zirconium dioxide) and the high temperature is needed for the electrolyte to attain sufficiently high conductivity. Because of the high temperature, internal reforming of the fuel gas (as with MCFC) is possible. Cost reductions in materials processing is strongly needed, and researchers may try to lower the operating temperatures of SOFC to below 800°C. Materials problems include high corrosion rates, and stress brought about by differing thermal expansion coefficients. At present, SOFC is the least developed of all fuel cell types.

Therefore, it can be summarised that materials innovations could be a technology enabler especially for PEMFC / DMFC, MCFC and SOFC. Problems in today’s fuel cell technology are associated with the high cost of materials and their processing, the availability of low-cost specific catalysts, sealing, thermal cycling, corrosion and reliability problems (see also field fuel cells in the roadmap on page 64).

Recently much effort is being put into fuel cell development for mobile applications. The vision is the “zero-emission vehicle”. But not every fuel-cell system and infrastructure would be more beneficial than today’s conventional drives. Fuel cells would only be part of a future sustainable economy, for example, if the hydrogen fuel would be produced via non-CO_2-emitting energy technologies. The fuel cell vehicle is basically an electric vehicle were the battery is replaced by a power generating fuel cell. The best developed fuel cell system for vehicles is the PEMFC and as stated previously, this fuel cell type has to be powered with almost CO-free hydrogen and air. Hydrogen storage in vehicles and its distribution to service stations is still an unsolved problem. Therefore novel materials for hydrogen storage, direct methanol fuel cells and the development of energy-efficient reformers are other important topics. In the 5th Framework Programme, the EU tried to overcome the technological barriers of fuel cells with projects such as "HYTRAN", "ZeroRegion" and "CUTE". Within the 6th Framework Programme, more than 40 projects are aiming at the improvement of fuel cell technology and the application of this technology. The "European Hydrogen and Fuel Cell Technology Platform" has published a roadmap, "European Roadmap for the development and deployment of H_2 and fuel cell technologies", (timeframe 2007 to 2015) in which materials innovations play a key role to develop MCFC and SOFC for combined heat and power applications as well as power generation[44].

Figure 18. Volkswagen high-temperature fuel cell (photo taken at the Hanover Trade Fair, 2007).

Although a hydrogen-based economy would have many obvious advantages, the distribution, transport and storage of hydrogen remains a critical problem. Pressurised hydrogen takes a great deal of volume compared to today's petroleum or gasoline - about 30 times more volume at 100 bar[45]. Condensed hydrogen is 10-fold denser, but it is too expensive to produce and there are safety concerns. Research is therefore going on to find suitable materials for hydrogen storage such as carbon structures (fullerenes, nanotubes), metals and metal alloys.

A promising method for hydrogen storage is seen in the formation of hydrides by the reaction of hydrogen with the atoms of the energy storage material. To enable high energy efficiencies the hydrogen has to be released from the storage medium with minimal energy consumption[46]. Binding energies make it very difficult to find a medium with a high hydrogen storage density and yet easy hydrogen release. Researchers are currently focussing investigations on metal-organic framework (MOF) compounds[47]. MOFs consist of metal-oxide clusters connected by organic linkers and are a relatively new class of nano-porous material which shows promise for hydrogen storage applications because of their tuneable pore size and functionality. MOFs might even be used for CO_2-storage too, since so-called “MOF-177” has the highest carbon dioxide capacity of any porous material yet known. More recently, covalent organic frameworks (COFs) have also been discovered, which have similar properties to MOF but do not contain metals.

Whereas in the short-to-medium time range improving energy efficiency is an important strategy, in the long run it is important to find non-CO_2-emitting renewable energy supplies to serve the exponentially growing world energy demand. Figure 19 gives an overview of renewable energy sources.

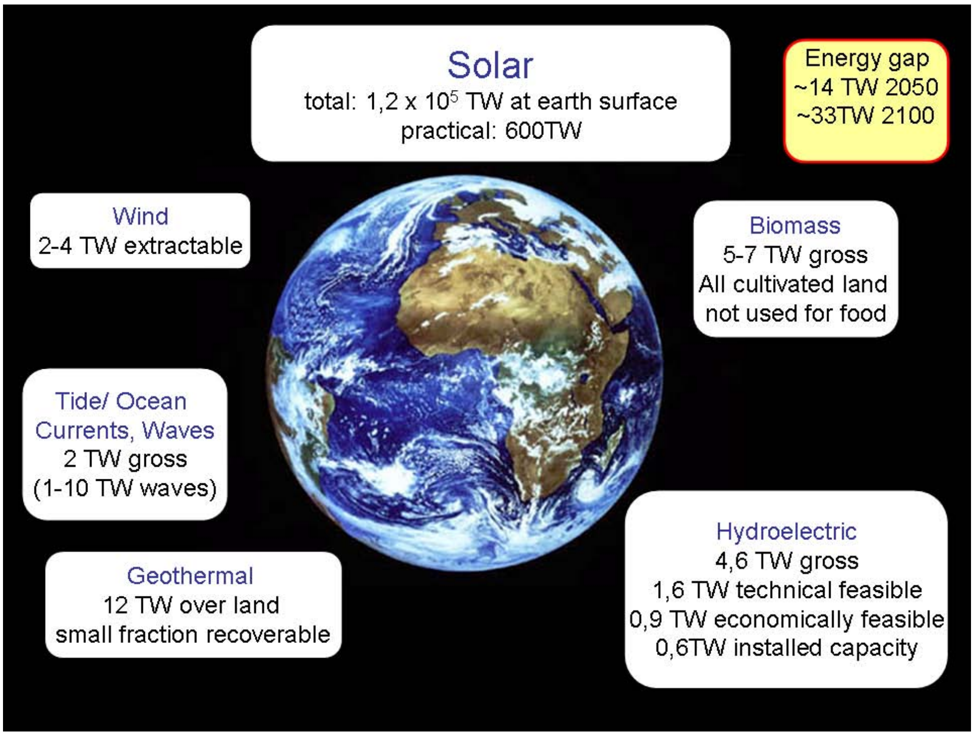

Figure 19. Ways to fill the world energy gap. In 2006, 14 TW of energy were utilised worldwide. Data and analogous figure from Professor Kilner (picture of earth from the ESA)

Wind Energy

Figure 20. Wind generators (photo: Gerd Schumacher)

As mentioned previously, wind power can only deliver a small fraction of the global energy demand. Wind turbines convert kinetic energy into electric energy. The characteristics of a 5-MW wind turbine machine are that it has a rotor diameter of 120m, which requires a high strength to weight ratio[48]. There are even installations with 200m rotor diameters in discussion, in which case blades would weigh around 50 tons[49]. In principle, a wind turbine consists of a rotor that has wing shaped blades attached to a hub which houses a drive unit consisting of a gearbox, connecting shafts and the generator. The hub-rotor system is positioned on a tower, which is fastened to the ground or even seabed. For wind turbines, the power generated increases with the square of the rotor diameter, whilst the mass of the blades increases to the third power of the rotor diameter if the dimensions are simply scaled up (the “square-cube“ law)[50]. Therefore, rotor design, new materials and the modelling of materials behaviour are critical factors for the development of advanced wind turbines.

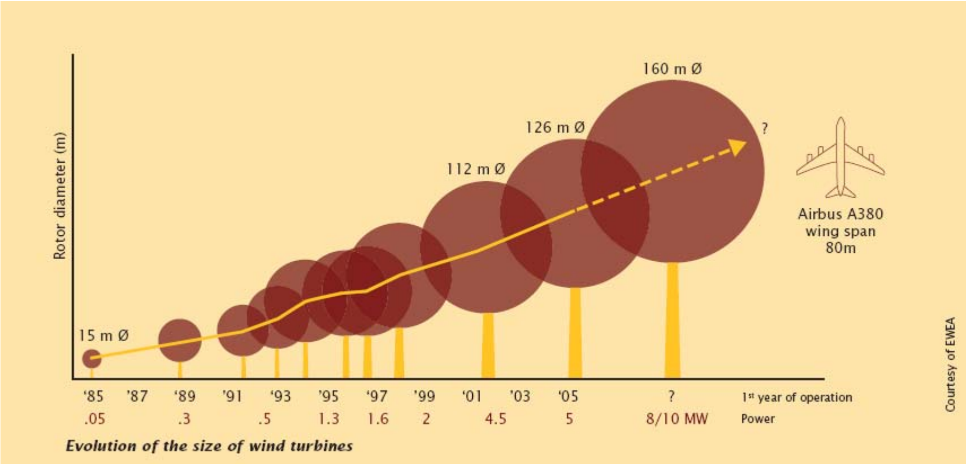

Figure 21. Growth in the diameter of wind turbine rotors during the last 20 years (taken from Renewable Energy Newsletter [51])

Today, most wind generators are positioned on tubular steel towers[48], manufactured in 20 – 30 metre sections (although, lattice towers or concrete towers are also used[52]). The rotor blades of most wind turbines are made of glass reinforced plastics (GRP, the plastics being polyester or epoxy). Other promising materials are carbon fibre-reinforced plastics, which are emerging but still expensive. Only in a few rotor types are wood / epoxy laminates strengthened by carbon fibre used (i.e. for some 1.5 MW turbines). Aluminium alloys and steel are only used to construct the blades of very small turbines because of weight and fatigue problems[52]. Interestingly, textile researchers are hoping to be able to develop blades from technical aramide textiles[121].

Developments in glass-reinforced plastics are targeted towards weight and cost reduction. Advanced joining techniques could allow blades for future installations to be transported in sections, which would lead to great cost reductions. Also, these techniques could allow the combination of composites with metals, which would widen the opportunities available for wind turbine design. Important for the design of future concepts is also the optimisation of scaling results from test specimens to fully sized components. Finally, materials degradation and testing are key issues for which non-destructive examination (NDE) and life assessment are important tools. A better understanding of the effect of spectral loadings on fatigue life is needed. Environmental degradation covering subjects such as the effect of moisture absorption by the matrix leading to surface crazing is another research field requiring attention.

Because of the limited capacities for wind power on land (onshore), where possible, wind parks are now moving offshore. Offshore installations are a great technical challenge[53] and stiffness and fatigue strength of the constructions play a key role. Since the immediate environment of offshore installations contains water and salt and there are usually higher UV emissions to endure, higher corrosion, erosion and stress corrosion resistance is required and resistance to UV exposure and good impact resistance are important issues for materials research.

In 2005, Europe had already installed a capacity of 34 GW and the continent is the leading manufacturer of wind power with a market share of 90%. In the future, the USA plans to cover 20% of their electrical energy demand through wind energy[54].

Hydropower, Tidal and Wave Power

Hydropower is an established technology that already accounts for a significant fraction of global electricity production. It can be obtained from potential energy (reservoirs) or kinetic energy (e.g. rivers). Hydropower electricity is mainly generated by passing the water through large water turbines, with modern water turbines having greater than 90% efficiency. The worldwide hydroelectric capacity in 2005 was 700 GW, with the USA (80) and Canada (67) being the biggest producers. Tidal power is a special form of hydropower that exploits the motion of the tides. Tidal barrage systems trap sea water in large basins (tidal lagoons) and the water is drained through low-head water turbines. The first large scale tidal power plant was constructed in 1966 in La Rance (Brittany), France with a capacity of 240 MW. In recent years, rotors have been developed that can extract the kinetic energy of underwater currents; these underwater rotors work in a similar manner to wind turbines. A major problem is to build stable systems that can withstand violent sea conditions.

The energy in a surface wave is proportional to the square of the amplitude and typical ocean waves transport about 30 - 70 kW of power per metre width of wave-front[55]. Therefore, also devices that harvest the energy from waves have been investigated. Most of the best sites for tidal power generation plants are on the western coastlines of continents between the 40° and 60° latitudes. Lifetimes of greater than 100 years is a requirement, but concrete steel reinforcement corrosion is a problem[48]. Materials barriers that have to be overcome include chloride attack which destroys the passive layer normally present under alkali conditions. Also, the carbonation of concrete produces acid conditions. Possible remedial measures include cathodic protection, polymeric coatings or corrosion inhibitors in the concrete.

Materials issues for hydro turbines are corrosion-related and are mainly caused by stress and fatigue. To enable hydropower to be utilised more often worldwide, research into low-cost C and C-Mn steels (adequate for many components) and the extensive use of stainless steels for critical components has to be undertaken. To avoid silt erosion and cavitation erosion, advanced coatings technology will be necessary to be applied.

Similar to nuclear energy technology, hydropower often causes public controversy because of the risk of collapse and the necessity of relocating citizens in the construction stage (so far, more than 30 million people have been forced to move worldwide). In addition the costs for the construction of dams are much higher than those for fossil fuel plants and, analogous to nuclear power, the cost for decommissioning at the end of their useful life are similarly high.

Biomass and Waste-to-Energy

Every EU citizen produces about 500kg of waste per year, so that in the entire EU 225 million tons of waste are produced annually. There are several different ways to manage this waste such as landfill, recycling and conversion to energy. Due to regulations in most developed countries, landfill is declining more and more. Some fractions of the waste can be successfully recycled such as aluminium cans, glass, paper and fibres. Waste-to-energy is a strategy to convert waste to energy.

Experts in the SMART project tended more towards realising a zero waste society (see “Materials Improving our Life” chapter) by utilising biodegradable packaging materials. Waste-to-energy can be sustainable if high amounts of the waste are from renewable bio-based products, since the amount of CO_2 released through combustion will be consumed by the renewable source. However, the waste to energy technology of today is a highly sophisticated technology and an important alternative to landfill; the latter often resulting in methane release, a greenhouse gas which is 23 times more dangerous to the climate than carbon dioxide[56].

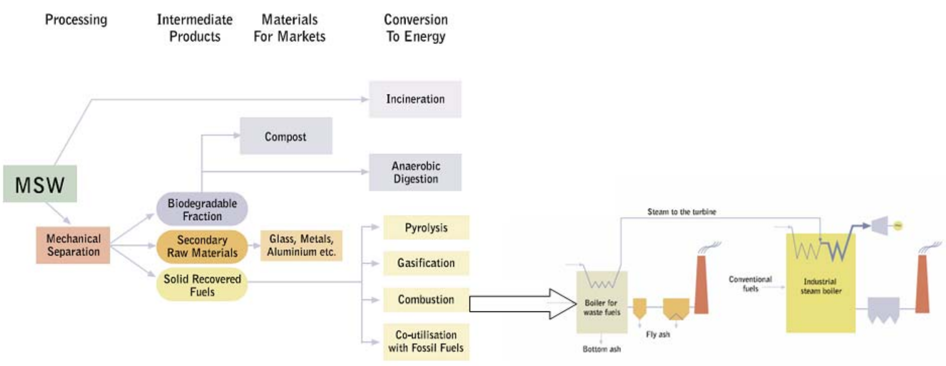

Figure 22. Waste Management; MSW = municipal solid waste (taken from IEA "Bioenergy")

Materials issues cover developments in the prevention of superheater tube corrosion. Currently, the efficiency of the combustion process is limited because steam conditions above 400°C and 40 bar would increase superheater corrosion. The target for superheater materials development is to provide corrosion-resistant materials which could operate at 520°C and 100 bar pressure. Low-cost tubes are needed for the replacement of the carbon steels used today. High Cr, Ni-based steels with up to 8% Mo seem to be best alternatives, although other candidates are coatings for alloy 625.

Biomass is defined[57] as: *"…the biodegradable fraction of products, waste and residues from agriculture (including vegetal and animal substances), forestry and related industries, as well as the biodegradable fraction of industrial and municipal waste...".*

Biomass represents an important sector of renewable energy, with the potential to supply 65% of the total renewable energy available to Europe. The European Union's

(EU-25) total land area is around 385 million hectares, of which woodland cover 140 and crop fields 180 hectares. Biomass from these trees and crops could theoretically deliver 11% of today's energy needs. But since the world population continues to grow, these land resources will most probably have to be used for agriculture for food production.

Biomass can be used to produce a wide variety of product types such as heat, electricity, solid fuels, liquid transport fuels and gaseous fuels. More than 80% of biomass comes from wood, 13% from municipal waste and only 2% from biogas. Recently, biomass to fuel (btl[9]) processes are being seen as promising alternatives to fossil fuels in the transport sector to overcome shortages in gasoline supply.

To produce electricity (or combined heat and power - CHP) from biomass, the biomass has to be converted to heat by combustion. The heat is used to produce steam which then drives a turbine. In advanced biomass installations, the biomass is converted to hydrogen, biogas or methanol and is used to operate fuel cells. Usually, biomass-based power plants are below a size of 20 MW. In many plants, co-combustion with coal in utility boilers is becoming a favoured option for wood fuels. Corrosion in such plants is highly fuel-specific, e.g. the highly corrosive alkali chlorides are produced from straw and there is no consistent correlation between corrosion rates and the Cr, Ni contents of the alloys being used. The corrosion rates can be reduced by co-firing, since sulphur in coal produces sulphates, which are less corrosive than chlorides. Also, reduction by the injection of ammonium sulphate is possible, which also converts the alkali chlorides to the less-corrosive sulphates.

Other processes to convert biomass to products and energy besides combustion include thermo-mechanical processes such as gasification and pyrolysis or biological methods such as anaerobic digestion. Gasification is a high-temperature process which is carried out under conditions that result in the production of a combustible gas[Fehler! Textmarke nicht definiert.]. In the process part of the biomass is combusted between 1200 and 1400°C under restricted air or oxygen supplies, resulting in the generation of a mixture of carbon monoxide, hydrogen, methane and carbon dioxide. This gas can be directly burned to produce heat or electricity or be fed to a gas

[9] Type of gasoline: btl = biomass to liquid

turbine. In gasification plants materials corrosion problems are more severe than in combustion plants, because of the highly reducing conditions prevalent[48]. Also, trace elements, tars, ash etc can cause potential corrosion problems in gas turbines, so that (hot) gas cleaning is needed.

Geothermal

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

Solar

Figure 23. Solar Thermal Central Receiver Systems (SIREC)[58]: In this plant in Andalusia, Spain, a high-flux receiver (2 MW/m^2) has been installed, which has a compact design and a ceramic absorber This device operates at temperatures of 1000 ºC and has a self-regulation system to adjust air recirculation flow rates.

Solar energy reaches the earth's upper atmosphere at a rate of 1366 W/m^2. The radiation is used in different technologies such as solar hot water systems, solar chemical processes, photovoltaics and solar thermal electric power plants. In Figure 23, such a solar thermal electric power plant with a solar power tower is shown, which uses a field of two-dimensional movable mirrors (heliostats) to focus the sun's rays upon the collection tower, where the high energy of the concentrated sunlight is transferred to a working fluid for conversion to electrical energy in a gas turbine.

Besides solar thermal electric technology, photovoltaics are seen as one of the most promising ways to produce sustainable energy since the energy produced by the sun seems to be almost inexhaustible[59]. The best way to convert the sun's energy for practical uses is to use the photovoltaic effect, an effect known since 1839 and discovered by Becquerel. A photovoltaic device (solar cell) converts adsorbed photons into electric charges that are used to energise an external circuit. Silicon solar cells play the most important role in today's photovoltaics market, for which the drivers are the search for new and better materials, the lowering of production costs and the striving for higher efficiency[60]. Materials research focuses on new inorganic materials for thin-film solar cells, organic based photovoltaics, multispectrum cells and dyes.

Today's solar cells are produced from crystalline silicon, which is doped to set up a p-n junction. Thus, on the one side an excess of positive charges (p-side, holes) is implanted to the material and on the opposite side an excess of negative charges (n-side, electrons). At the junction an electric field is therefore created. Light produces electrons and holes in the bulk Si material and these charges then diffuse through the material towards the electrodes. The photovoltaic devices in common use today are solar cells of the first generation which have a single junction. The theoretical maximum energy conversion efficiency of such cells is 31% and the best performances reached so far are shown in Figure 24. Today's photovoltaic installations still require improvement with respect to corrosion fouling resistance and collector abrasion.

Currently so-called "second generation" photovoltaics are approaching commercialisation[63]. These devices utilise thin-film technologies which do not necessitate the produced of wafers and therefore have reduced costs. The devices are based on materials systems such as CdS/CdTe, Cu(In,Ga)Se2 (CIGS), and multijunction a-Si/a-SiGe. They are fabricated using techniques such as sputtering, physical vapour deposition, and plasma-enhanced chemical vapour deposition. Multijunction cells based on a-Si/a-SiGe are the most successful second-generation technology to date because of their relatively low production costs. Some companies are producing a-Si/a-SiGe devices using roll-to-roll processing on flexible stainless steel and other substrates that permit high-speed production[63].

The long-term vision is to develop cells with a higher efficiency-to-cost ratio. According to Figure 25, there are two ways to reach such third-generation devices. The first strategy is to use revolutionary physical concepts to develop cells with ultra-high efficiencies- above 50%. The second approach is to create solar cells with moderate efficiencies but at extremely low costs. Most experts today believe that the second approach could be realised through organic-based photovoltaics. Organic photovoltaics might play an important role as power sources in organic electronics for displays, smart packaging and actuators in the future. The advantage of organic solar materials is their low price and the opportunity to use low-cost, high-throughput manufacturing processes. A major problem is the stability of the conducting polymer.

Organic semiconductors function in a completely differently manner to inorganic semiconductors. In organic semiconductors, light produces excitons (electron-hole pairs bound together by coulomb forces) which have to be "disconnected" at either defect sites or interfaces leading to electron transfer from the donor material to the acceptor, or hole transfer from the acceptor to the donor. The organic-based cells still require significant R&D and face a number of challenges include increasing efficiency by at least 5%, the harvesting of a more energetic part of the electromagnetic spectrum by reducing optical band gaps, and higher charge mobilities. Furthermore, an improved understanding of carrier transport processes and the mechanism of recombination at interfaces is needed.

The other approach is the development of ultra-high efficiency solar cells. Physics and nanotechnology offer a variety of effects which might be used to realise solar cells with efficiencies greater than 50%, including multi-junction cells. Since a single junction cell can only absorb a certain wavelength of the spectrum, the remainder of the spectrum is not utilised and cannot be converted to usable energy. Therefore in multi-junction cells, a stack of cells with different band gaps is set up. Such multi-junction cells could theoretically have an efficiency of up to 70% and the first research results have shown improved efficiencies of up to 34%. Quantum dots / nanoparticles have advantageous properties for the development of ultra-efficient solar cells, since in nanoparticles the band gap is a function of the particle size and therefore tuneable. Another advantage of quantum dots is that they can be incorporated into an organic matrix, so that the resulting engineering material can be produced easily, and integration into devices is comparable to that with commonly used technologies. Multiple excitations from one photon are produced, which occurs when the absorbed energy is far greater than the semiconductor band gap[61]. This phenomenon has only been observed in semi-conducting quantum-dot materials[62]. Recently multiband-gap materials have been found that can convert several different wavelengths with a single junction.

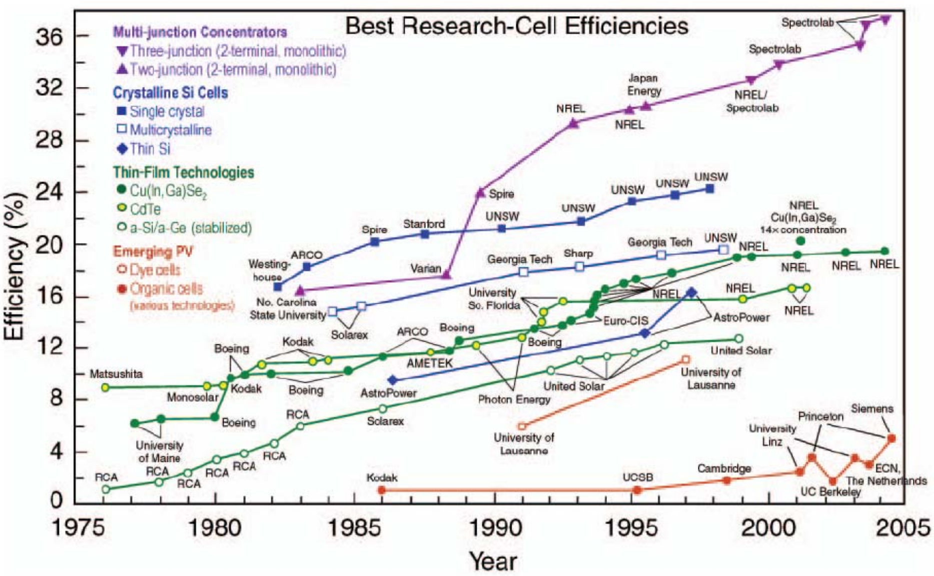

Figure 24. Best research cell efficiencies (from MRS[63])

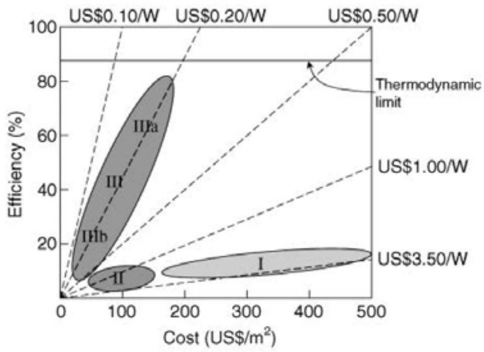

Figure 25. Expected efficiencies and prices (from MRS[63])

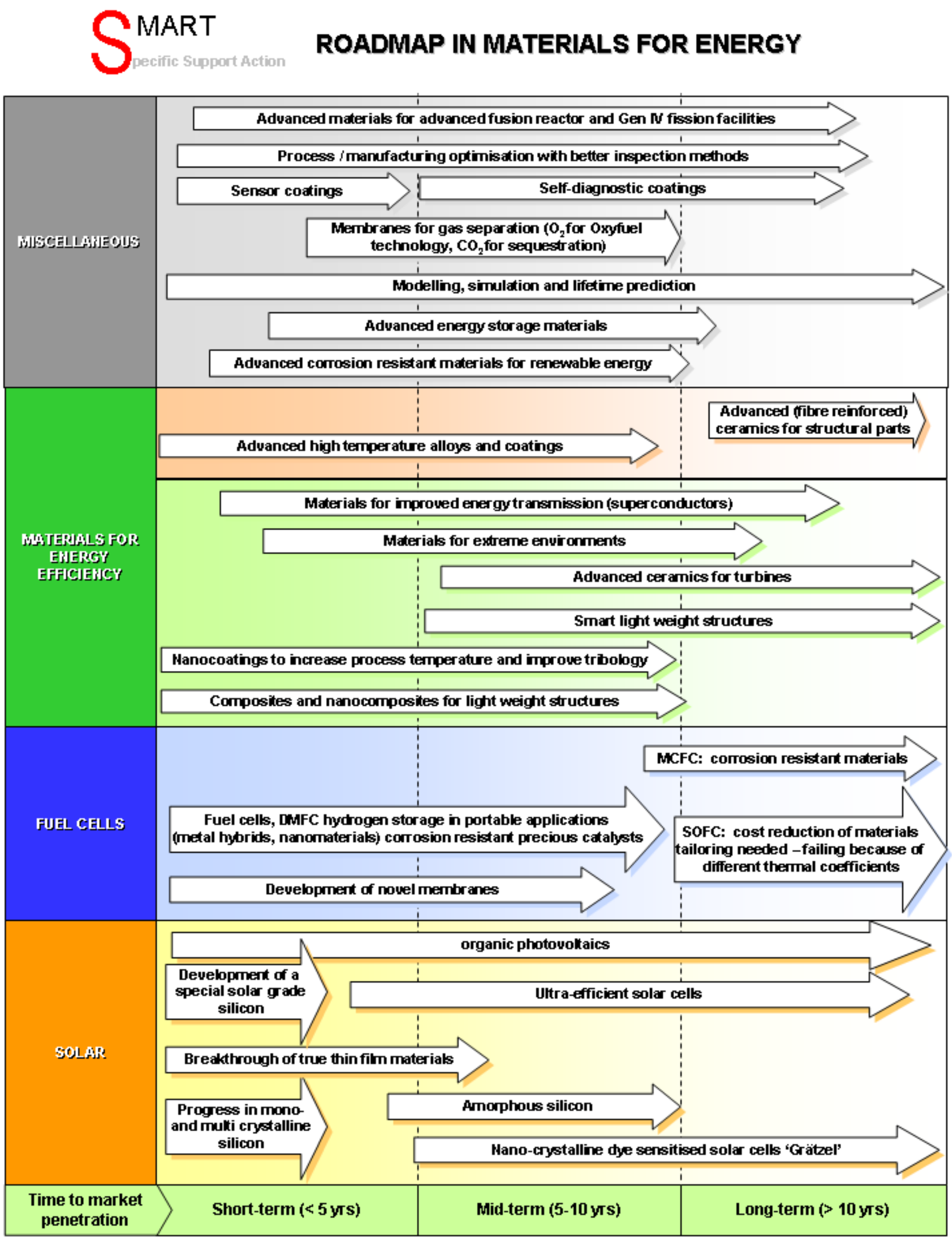

Figure 26. Roadmap "Materials for Energy"

Energy is a strategic resource for all industrialised countries so that the development of future energy technology is of great importance for Europe. Energy safety and CO_2 reduction are the main drivers in this field. The following research priorities have been identified:

- Innovative gas separation membranes for CO_2-capture technology
- Corrosion-resistant materials for energy technology in oxyfuel processes
- Materials for white light-emitting devices
- Polymers and materials processing for organic light-emitting devices
- Ferritic martensic steels, vanadium-based alloys and fibre-reinforced composites for future fusion technology
- Phase-change materials and MOF
- CO_2-reduction in mobility: light-weight alloys, nanocomposites and biocomposites
- Materials for superconducting devices
- Advanced corrosion resistant (less degradable) materials for various renewable energy sources
- Corrosion-resistant materials for SOFC
- Energy storage materials
- Advanced joining techniques for manufacturing wind-powered generators
- Ceramics for solar power tower technology
- Materials for 3rd generation solar cells

Roadmaps: Materials for a Safe Europe

To identify the innovation potentials for the field of "Materials for a Safe Europe", expert interviewing and a roadmapping workshop were carried out. Initially this field had to be characterised and it can be divided into personal protection, industrial safety, anti-counterfeiting and protection of the civil infrastructure. A special feature of this safety field is that most information is confidential. A paper by Toni Grobstein Marechaux gives an overview about the potentials of materials technology to reduce the threat of terrorism[64]. In the section *Products and Technologies for Citizen Protection* in the Strategic Research Agenda of the SusChem ETP; alarm systems based on stimuli-responsive materials, and thermochromic windows as well as innovative textile materials for protective clothing and NBRC sensors have been identified as future research priorities.

Textile materials play an important role in the area of personal protection, but information about this area will be mainly discussed in the section on "better life". According to the roadmap "Materials for a safe Europe" on page 76, the materials research topics can be categorised into materials for sensors and materials for protection. Therefore in the following two chapters the potentials in these fields will be considered in more detail.

Sensors

Figure 27. Robot for NBRC detection and mitigation of ammunition (photo from Diehl Stiftung & Co. KG)

Most experts identified materials research topics for security in the SMART process which are related to sensors and sensing (see blue topics in the figure on page 76). Therefore this important field will be considered here in detail.

For personal protection in households a spectacular innovation would be the application of intelligent carpets in order to protect the household against undesired visitors (e.g. burglars). After the household members leave the house, a security code would be switched on and the sensor-equipped carpet would be part of the house security system[8]. Similar optical solutions are already commercially available today, but pressure-sensitive carpets might be a good complementary device.

The areas of nuclear, biological, radioactive and chemical (NBRC) threats are taken very seriously as these substances could cause tremendous destruction and casualties on a large scale. The development of sensors for these threats, therefore, has a high priority. For applications in food quality control and environmental monitoring, electronic “noses” are already being used based on metal oxide semiconductor (MOS) sensor arrays[65], which are used to evaluate odours and malodours. Many metal oxides show gas-sensitivity under suitable conditions; the most widely used material is tin dioxide (SnO_2) doped with catalytic metal additives. The target is identified by its effect on the electrical resistance of the semiconductor. SnO_2-resistive sensors have been developed for a wide range of applications (such as hydrogen sulphide and ammonia sensors)[65].

Nanostructured materials play a key role in the development of advanced sensors[66], since the interaction of the target and the detection site takes place on the nanometre scale[67]. In the engineering of these sensors, an understanding of the target compounds is the first necessity. Some substances with low molecular weights such as chemical agents and toxic industrial compounds are volatile and may not persist for very long in the environment (e.g. sarin). Some of these substances are made more suitable for weapons by materials modifications, so that their life times are extended. Some biological threats include very large biomolecules such as ricin.

There are many examples of effective systems for detection and protection in nature. For sensors in particular, nature has numerous examples of detection at extremely low levels. In the future, nanotechnology and lab-on-a-chip techniques will enable the development of fast and more sensitive detection systems in which the sensor will be able to detect the presence of the target in difficult backgrounds and at very low concentrations. Nanomaterials play an important role in sensor development, since these sensors need a binding or interaction site. This site could be a molecular imprint, a templated solid or a covalent interaction. The interaction site also requires specificity for one certain class of compounds since the chemistry of the environment might be complex. A solution for such an interacting site is immobilised enzymes. Enzymes have the advantages of being very specific and their interaction with target molecules is reversible. In order to be effectively used, the enzymes have to be immobilised on a carrier (silicon or silica coatings) and the linkage between the enzyme and the surface of the platform is a materials challenge. The detection will be facilitated via conventional enzymatic chemistry (electrodes, photoluminescence, spectroscopy).

Figure 28. Mine clearance in the Democratic Republic of Congo. In many cases, the canine sensing nose is still superior to artificial sensors (United Nations Peacekeeping Photo Gallery)

Other approaches for interaction sites in sensors are silicon and polymeric materials. Porous silicon has been used for the detection of explosives. Polymeric materials and silica sol gels can be used as detection and collection devices by designing an interaction site through molecular imprinting during the polymer formation. The target is used for imprinting and then removed, leaving an imprint with the complementary structure of the target. Furthermore, the identification could take place by optoelectronic signals. In such system an array of multiple dyes would change their colour according to intermolecular interactions, which would then be detected by optical sensors[68].

Besides nano- and chemical sensors another approach is the use of spectroscopic sensors. in the electromagnetic spectrum, terahertz frequency is to be found in the range of wavelengths of under 1 mm down to several 100 micrometers. Terahertz (THz) radiation is non-ionising and can penetrate a wide variety of non-conducting materials such as clothing, paper, wood, plastic and ceramics. While also fog and clouds can be penetrated by terahertz rays, metal or water are opaque to THz systems. Security-related application areas for such systems include the detection of concealed weapons as many non-metallic, non-polar materials are identifiable with THz radiation. Many explosives (e.g. C-4, HMX, RDX and TNT) and illegal drugs (e.g. methamphetamine) have characteristic transmission and reflection spectra in the THz range which are distinguishable from other materials such as clothing, coins and human skin.

THz is a very promising technology since it does not pose health risks during the scanning of people[69]. The vast variety of potential applications of terahertz technology in medicine, industry and security is limited today, however, by the lack of the availability of high-power, low-cost, portable room temperature THz sources. A breakthrough in THz technology could be managed through advances in high-speed electronics, lasers and materials research[70]. Photoconduction and optical rectification are two of the most common approaches for generating broadband-pulsed THz beams. The photoconductive approach uses high-speed photoconductors as transient current sources for radiating antennas. Typical photoconductors include GaAs, InP and radiation-damaged silicon wafers. Another potential technique for the production of THz rays is to utilise the inverse electro-optical effect. For the optimisation of THz generation the electro-optic properties of different materials are being investigated and promising materials include semiconductors, such as GaAs and ZnTe, and organic crystals such as DAST[h] among many others.

Challenges for sensor development include the simultaneous measurement of different target components and increasing performance by monitoring different sensor parameters at the same time, and improving sensor stability with time. It is likely that various sensor types will be combined in the future (hybrid sensors).

Experts at the "Materials for a Safe Europe" workshop identified self-healing and self-checking detection systems as being needed. Also, standards for sensors should be established. Currently, in most parts of Europe R&D on sensors is particularly fragmented. Because of a high degree of interdisciplinarity of the subject, progress relies on a greater collaboration between those working on different types of sensors. Even though cheaper and more reliable sensors are being developed today, major steps forward could be achieved through THz technology and through the development of rapid, miniaturised methods of detecting DNA[71, 72].

Protection

New requirements for protection materials[73] include high elastic moduli compared with the ballistic threat. Thus low-density ceramics are promising materials for protective use. There is also a need to replace traditional bullet-proof glass with other transparent materials which are stronger and thus more capable of withstanding the threat. Here, nanotechnology is offering some promising solutions. New materials in development for protective use in vehicles include nanostructured ceramic materials, combinations of metals, hard metals, high-tech fibres and elastomers, new constructions of armour sandwiches and transparent armour concepts. New materials for construction play an important role in securing buildings and infrastructure against man made and natural disasters[74]. Fibre-reinforced polymer matrix composite materials could be used in the civil infrastructures ranging from the seismic retrofit of bridge columns and the strengthening of parking garage floor slabs to their use in replacement bridge decks and in new bridge structures[75, 76].

[h] Ionic salt 4-dimethylamino-N-methylstilbazoliumtosylate

There is a need for lighter weight and more easily wearable armour (or clothes generally) that offer protection from piercing, chemicals, impacts, radiation, etc. Interactive textiles have the potential to decrease risk for security personal and peace-keeping forces. With interactive textiles, it will be possible to have a penetration alert (detection of a bullet or shrapnel penetrating the shirt of the wearer). This can be achieved using plastic optical fibres, with penetration detected by a break in an optical fibre circuit. In this way, information can then be transmitted to the headquarters of the security unit and medical help sent.

Fibres for bullet-proof vests must have a number of chemical and physical bonds for transferring the stress along the fibre[77] and the fibres should possess high stiffness and strengths to limit their deformation. In fibre-reinforced composites, the fibres are the load-bearing element in the structure, and they must adhere well to the matrix material. An ideal reinforcing fibre must have high tensile and compressive moduli, high tensile and compressive strengths, high damage tolerance, low specific weight (grams per square metre), good adhesion to the matrix material and good temperature resistance. Fibres with such properties include polyethylene, aramide, polybenzobisoxazole (PBO), M5, and carbon fibres. The *para*-aramides (Kevlar, Twaron, Technora) are the best known examples. M5[i] is a very promising material that might also find applications in the automotive, aerospace and sports industries. Doetze et al. speculate that the high impact and damage tolerance resistance of M5 is due to the honeycomb-like structure of this polymer. Further protective applications of smart textile materials can be found in the better life chapter.

[i] Poly{2,6-diimidazo[4,5-b-4',5'-e]pyridinylene-1,4(2,5-dihydroxy)phenylene}, known as PIPD or M5.

Special aspects of materials developments for protection

By Dušan Galusek, Slovakian Academy of Science

The ever increasing efficiency of modern firearms represents a significant threat to law enforcement and peacekeeping forces. This threat affects the operability of vehicles and the life and health of individuals. The new types of ammunition (e.g. with tungsten carbide cores in small firearms, and kinetic penetrators, RPG's, chemically driven ammunition etc. in larger calibres) represent a significant threat due to their high kinetic energy, high hardness and resulting ability to penetrate easily into virtually any material. The attempts to counter such high-energy threats usually lead to unacceptable increases in the thickness and weight of armours, which is a limiting factor both in human body and in vehicle protection. The low-weight imperative resulted in replacement of steels (as traditional armour materials) by ceramics, leading to layered armour concepts. These consist of an ultra-hard ceramic impact layer, which decreases the kinetic energy of a projectile by shattering and eroding it. The underlying plastic (often metallic) layer absorbs the residual kinetic energy of the projectile by plastic deformation. Ceramic materials, such as Al_2O_3, SiC, TiC, B_4C, therefore became the materials of choice for modern armour concepts.

The major challenges for protective armour materials of the future can be summarised as follows:

- decrease of thickness and weight at comparable or higher levels of ballistic protection and acceptable price;
- increased modularity, protection-on-demand concepts where the armour system is adjusted operatively to the expected type of threat, easy-to-replace armours for quick replacement;
- increased multi-hit resistance of ceramic protection;
- floating armours;
- really efficient transparent protection materials.

There are several important obstacles that have to be overcome:

- There will be probably no "miracle" material available in a foreseeable future, and the threats will have to be countered with what materials we have today;
- There is no general agreement on which properties an "ideal" armour material must possess: the uncertainty stems from a very complex nature of interactions between the threat and the armour;
- There are significant gaps in understanding the nature of interactions between threats and targets under dynamic loading conditions.

It has been generally accepted that armour must posses a high hardness and a high elastic modulus, under the conditions of dynamic loading expressed in terms of the so-called "Hugoniot elastic limit". This simple rule has been challenged recently by Krell and Strassburger, who attempted, on the basis of the analysis of bullet - armour interaction, to establish a hierarchy of key parameters influencing the ballistic strength of ceramic armours[78]. The authors define two periods of the bullet - armour interaction:

1. A short initial phase (<10 μs), where high dynamic stiffness (determined by Young's modulus) of the impact layer overmatches the impact load and causes the nose of the projectile to dwell on the ceramic surface without penetrating it in the first moments. It is, therefore, expected that Young's modulus is most important in this phase.
2. The penetration period, which starts about 10-15 μs after the first contact with a relatively low penetration velocity. This period involves erosive wear and fragmentation of both the penetrator and the surrounding ceramic armour. In this period the inertia (related to their size) of ceramic fragments and their hardness are believed to play a decisive role in slowing down the penetrator and to erode it, thus robbing it of the major part of its kinetic energy. How to achieve controlled shattering of the ceramic armour material to the fragments of controlled size remains to be answered by future research.

Some promising solutions are offered by the application of nanotechnologies:

- The use of nano-structured ceramic materials, i.e. monolithic materials with sub-micrometre grain size prepared by advanced sintering technologies such as spark plasma sintering, hot isostatic pressing, sinter-HIP, or microwave-assisted sintering, and their composites reinforced by nanoparticles or nanofibres, e.g. carbon nanotubes.
- New concepts of layered armours, and combinations of ceramics with metals, hard metals, high-tech fibres, elastomers and liquid polymers (e.g. the recently reported concept of liquid armour of polyethylene glycol with dispersed silica nanoparticles, known as shear-thickening fluid, which becomes rigid under applied stress, yet reverts to being soft and flexible when the stress is removed)[79]

In order to increase the ballistic efficiency of armours a multidisciplinary research effort will have to focus on:

- Fundamental research leading to the ultimate understanding of the behaviour of solids under dynamic loading conditions;
- The modelling and computer simulation of interactions of high-energy penetrators with high-hardness and high-moduli substances;
- The optimisation of the properties of existing materials, scaling down to nano-level structures with possible outcomes of specific properties not attainable in micro-scaled structures;
- The development of new methods for the joining of fundamentally different materials;
- The development of fundamentally new concepts and constructions of armour sandwiches

Smart materials play an important role in the development of security systems. In this R&D-area, engineers are applying bionic concepts for implementing smart materials systems into engines. Smart materials are materials systems that can sense external stimuli and respond with active controls, in real or near-real time, to change their properties[80]. This change in properties allows the structure to dynamically adapt to its environment and to tailor its response. Smart materials function analogous to biological systems, where the brain, senses and muscles work collectively. Smart material systems have been used to reduce acoustic emissions in underwater applications and helicopter blades. By applying shape-memory alloys to wing-structures, smart wing systems can be constructed which can be used to reduce radar signatures. Certain actuator materials (such as PVDF, PZT, SMA, dielectric elastomers) are used for robots and unmanned aerial vehicles. A bottleneck in smart materials developments for security applications is to find an actuation material with similar characteristics to the human muscle. However, in order to develop a robot which truly moves and acts on biological principles, one needs to fully emulate the dynamics of the muscle. Wax et al.[80] demonstrate this by the example in which long before a person realises the terrain has switched from ground to sand, a person's legs have reacted and adapted. This is because a significant part of the feedback system for biological locomotion actually occurs in the muscles themselves. Not only do muscles act as actuators, but they also serve as sensors providing local position information. Electroactive polymers (EAP) are a promising material in the development of advanced actuators for robots (further information about EAP is given on page 106). In the very far future the vision is to obtain a smart material that shows self-healing properties.

Radio Frequency Identification (RFID) is a technology for the automated identification of objects and people[81] and is also foreseen for some security-related application areas. RFID devices are small microchips (some 0.4 mm) designed for wireless data transmission. It is generally attached to an antenna in a package that resembles an ordinary adhesive sticker. In contrast to barcodes, RFID tags are readable without line-of-sight contact and without precise positioning. The information they contain is encrypted in electronic product code (EPC) standard. There are two different types of RFID tags: small and inexpensive RFID tags (less than 10 cents per unit), which are passive and derive their energy from the scanning signal in the reading process and active RFID tags which contain batteries and can cost up to € 15. Already today, RFID is an important application area for printed electronics since antennae are produced this way. However, in the future it is predicted that transistors and batteries for RFID devices will also be produced by printed electronics. Therefore advanced polymers for printed electronics are a critical research topic for future progress in RFID. In addition to household and convenience applications including providing information on the optimum washing procedure in washing machines, and warning customers that expiration dates have passed in packaged food, as well as in toll payment tags and tags at libraries, there are also potential security-related applications such as within passports for authentication and in products to battle counterfeiting. At the SMART workshop, experts were impressed by the potentials of such technologies but at the same time indicated their concern about overt state control and the erosion of citizen privacy.

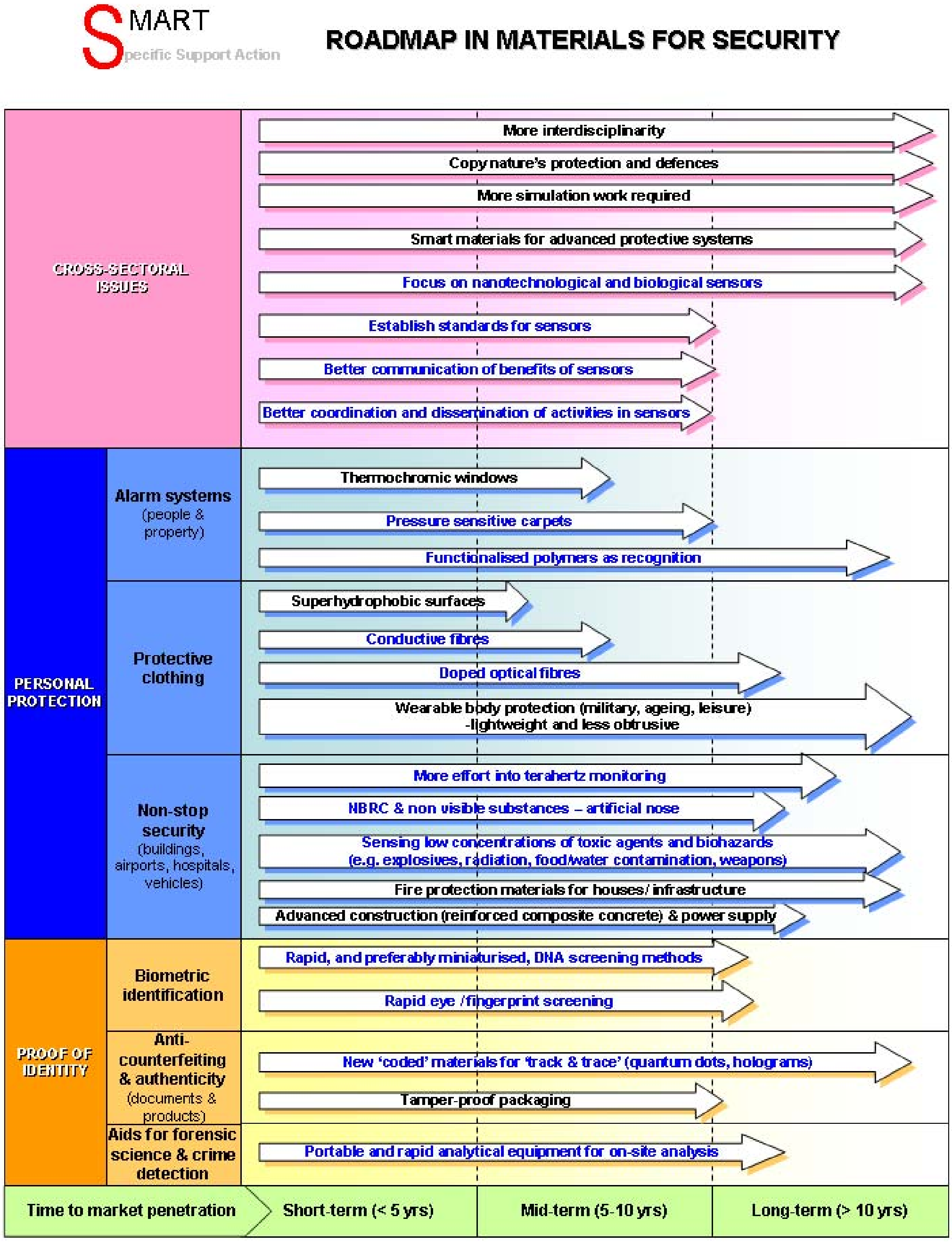

Figure 29. Roadmap “Materials for a Safe Europe”

In conclusion, it can be seen that whereas materials for security applications are not at the forefront of security research, materials research is a technology enabler for the area of sensors and scanners and at the same time could also be an important factor in making these technologies widely available. Smart materials, polymers and nanomaterials are on the way to revolutionising security technology in the area of protection by innovative armour and in the field of anti-counterfeiting. Because the threats of terrorism, various peace-keeping missions world-wide and anti-counterfeiting of European products are relevant areas for European politics, materials research priorities are:

- Smart materials and nanomaterials research for protection as well as for the development of sensors to improve the security of European citizens and peacekeeping forces
- Advanced polymers and nanomaterials for anti-counterfeiting systems to secure Europe’s global market position in high value-added products.

Roadmaps: Materials Improving our life

To identify the innovation potentials in the field of materials aiming at improving the life of humans, extensive literature research, expert interviewing and a roadmapping workshop were carried out. First of all this field of *materials for a better life* has to be characterised. In this field, biomaterials for medical applications, electronic materials for information, communication and entertainment, textile materials for clothing, construction and medical applications and materials for packaging play an important role. While detailed information about electronic materials for the information and communication sector is available through the International Technology Roadmap for Semiconductors (www.itrs.net/) and the Roadmaps of the International Electronics Manufacturing Initiative (www.inemi.org), all other areas were considered in detail in the SMART foresight process.

In 2003, the Materials Panel for the UK Government's Foresight exercise produced a booklet entitled "Smart Materials for the 21st Century"[82]. This foresight study is mainly focussing on materials research topics that are relevant for the area of materials for a better life, therefore the study focuses on agriculture, food and consumer packaging, construction, sports and leisure, white goods and domestic products and healthcare. The study Smart Materials for the 21st Century states that materials technology has to be developed that provide pragmatic and cost-effective solutions to smart labelling and packaging. Europe already has expertise in this area, and is well placed to exploit smart materials technology in the implementation of traceability protocols to improve food quality and safety. Barriers to the exploitation of smart materials in this sector are given as improving materials properties, system compatibility, availability and cost, better awareness and acceptability of smart materials in traditional engineering sectors. Spin-off from other sectors needs to be achieved. Generally, the smart materials systems under development cover speciality polymers, coatings, adhesives, composites, inorganic materials, metals, biotechnology and biomaterials. Other key developments are the investigation of the bio-interactive behaviour of materials and the development of bio-compatible components and devices. Important expected developments in the area of healthcare include adjustable stents and catheters, microbial resistance, smart surgical tools and neurosensor prosthesis.

In 2005 and 2006, a strategic research plan and an implementation action plan were published by the European Technology Platform SusChem[83]. For this purpose, roadmaps for materials for the electronics industry (communications, information, entertainment), materials for medicine, agriculture, nutrition (healthcare) and materials for the enhancement of the quality of life were developed. In the field of materials for medicine, the identified fields are tissue engineering, smart delivery systems, targeted drug delivery, functional textiles and bone reconstruction. New materials for implants, drug delivery, novel therapeutics, health protection and care, diagnostics and sensors for prevention and detection are further relevant fields.

In 2004, the Copper Development Centre sponsored a Building Construction Technology Roadmap in Australia. In this roadmap, the development of smart windows is foreseen. Such windows would have integrated photovoltaics and OLEDs and could be used for holographic imaging; they also would be switchable between transparent and opaque.

Considering materials for a better life in this study, the field was divided into biomaterials (and materials for medical devices), materials for packaging and high-tech textiles. Roadmaps were created based on data screening, expert interviewing and on discussions and statements at the expert workshop in Lisbon in October 2006.

Figure 30. Participants of the roadmapping workshop "Materials for a Better Life", which took place in October 2006 in Lisbon

Biomaterials and Materials for Medical Applications

In the results of the review analyses on page 29, biomaterials are basically identical with “Bioconceptional Materials” and ”Soft Matter”. Therefore, almost 40% of recent review papers deal with this matter and state that this research field is of great potential for the future. In 20% of the interviews of experts, the field biomaterials was mentioned as being a hot spot of their research work.

A commonly used definition of biomaterials is, that these are nonviable materials used in a medical device, intended to interact with a biological system. Biomaterials development is mainly linked to medical applications. The healthcare market covers hip and knee prostheses, vascular grafts[j], heart valves, percutaneous devices[k], stimulatory electrodes, catheters and stents[l]. Therefore materials innovations are a key factor for the competitiveness of medical companies and breakthroughs in healthcare.

A main part of the biomaterials roadmap in Figure 35 describes materials innovations needed for the development of next generation implants. The development of next generation implants[84] can be divided into the improvement of existing implant materials, the medium-term development of artificial improved implants by smart materials and the long-term vision of regenerative medicine. However, even though the improvement of existing implants is a priority task, the focus of materials research for biomedical applications is expanding from materials just being inert and passive in the body to materials with a higher functionality, so that these materials can interact with the body in specific and predictable ways. As well as implants, materials innovations for medical devices such as smart surgery tools and prostheses are part of foreseen materials-relevant developments in the future.

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[j] A vascular graft is a man-made tube which replaces or bypasses part of a blood vessel, most commonly an artery (source: www.terumo.co.jp).

[k] The percutaneous approach is commonly used in vascular procedures. This involves a needle catheter getting access to a blood vessel, followed by the introduction of a wire through the lumen of the needle. It is over this wire that other catheters can be placed into the blood vessel (source: www.wikipedia.org).

[l] Stents are very small wire scaffolds that are placed in the coronary arteries of patients with narrowed blood vessels.

Improvement of Existing Implants and Medical Materials

The human body reacts to today's implants by encapsulation and walling off since these implants are identified by the human immune system as foreign intruders. To solve this problem within the next years for today's implants, the improvement of *biocompatibility* in the development of tailor-made materials for interaction with biological systems[85] is needed. The European Society of Biomaterials defined biocompatibility as "the ability of a biomaterial to induce the appropriate answer in a specific application". To enable progress in existing implant materials technology, antibacterial surface treatments, non-fouling surfaces and controlled drug release strategies have to be developed in the area of materials research. Basic research on protein interaction is also needed. The goal is to reach improvements in the biocompatibility of implants between the component and the body in order to reduce rejection or infection.

Polymers for medical applications are already in use since 1937, in particular PMMA [poly(methyl methacrylate)], which was used initially in dental prostheses and later also used for eye surgery (ophthalmics). More and more innovative polymers play an important role in the development of medical devices, today. The global consumption of polymers in medical technology is dominated by PVC, with polyethylene, polypropylene and polystyrene being next in order. Technical polymers such as polyesters, ABS and SAN, polycarbonate and TPE are used in much smaller quantities. In the last years, there has been a trend to replace glass in medicine and pharmacy by polymeric systems, as seen with contact lenses, membrane modules, and catheters. Christian Oehr[85] stated that the volume properties of polymeric materials have to be chemically and mechanically stable in a biological surrounding. Furthermore, these materials should not be allowed to release remaining monomers, additives, or auxiliary materials. Also, such polymeric materials must withstand sterilisation procedures and in some cases (e.g. diagnostics) should have excellent optical properties.

A relevant research area for improving existing implant materials are surface modification technologies. Surface properties are a key factor in implant development, since they control the blood and tissue compatibility of a biomaterial.

Surface manipulation can be used to optimise a variety of material characteristics, such as increasing the lubricity of materials, increasing the durability or wear resistance of materials, improving the resistance of materials to clot formation and decreasing the susceptibility to infection[86]. Relevant surface modification techniques are low-pressure plasma treatment and chemical grafting. Low-pressure plasma treatment is, for example, used to increase biocompatibility. Chemical grafting is a technique that uses wet chemistry to attach new chemical species to material surfaces (mainly used to improve biocompatibility). Therefore anti-clotting agents (such as heparin) are coated to the surface. The coating process itself is a complex chemical process in which a hydrogel is used. Such non-clotting surfaces have been applied to blood-contacting devices such as oxygenators[m], vascular stents, catheters and vascular grafts.

Artificial Solutions with Smart Materials

In the mid-term range, the development of artificial tissue and organs can be expected. These artificial human body parts might in some cases even have a superior performance compared to the original natural parts. More than 100 million humans carry at least one major internal device today. Even though many new materials are under development for biomedical use, today only a dozen materials are in use to construct artificial organs for internal implantation. The cause of the limited use of innovative materials for medical applications is the limited availability of materials and the necessity to match challenging constraints[87]. Before innovative materials can be introduced to the medical market, successful testing of biocompatibility by in vitro studies, in vivo studies and clinical studies is needed. Therefore, the development of biocompatible surfaces is a critical bottleneck. In visionary approaches even the construction of artificial muscles by electroactive polymers (see page 106) seems possible with smart materials.

[m] Oxygenators are devices which mechanically oxygenate venous blood extracorporeally. They are used in combination with one or more pumps for maintaining circulation during open heart surgery and for assisting the circulation in patients seriously ill with some cardiac and pulmonary disorders (source: http://cancerweb.ncl.ac.uk).

Smart materials for implants cover stimuli responsive materials, shape memory alloys[n] and materials with high superelasticity[86]. Some smart materials applications are already in medical usage today, such as endovascular stents, orthopaedic staples and dental braces. Medical applications of smart materials are not limited to the construction of implants, however. Such alloys can also be used to reach confined places in non-invasive surgery. The instrument handles can be bent with enormous precision to the proper shape required for surgery, and recover their initial shape after heating (shape memory alloys).

In the area of shape memory alloys, most R&D work has been carried out in the field of NiTi alloys (Nitinol), but also CuZn, AuCd, CuSn, TiPd, NiAl as well as NiTiCu and CuZnAl are under investigation[87]. The challenge for materials engineers is to predict the behaviour of the shape memory alloy in a specific situation- a function of geometry, environmental conditions (such as temperature) and force. This accounts for the long time for technology transfer. NiTi had been the subject of undergone extensive investigation in the 1970s, but it took another 20 years for the first commercial NiTi stent to become available.

Nickel-titanium alloy is an almost magic material, which has a spring-back property that is 20 times greater than that of stainless steel and has good biocompatibility. NiTi can be used for self-expanding and self-compressing medical devices. These alloys are used in wires of braces in dentistry and for smart devices in orthopaedics such as self-expanding screws and staples. Also nickel-titanium alloys are in development for highly sophisticated stents that provide more assurance that the stent will stay open and can be applied in critical conditions such as an aneurysm of the aorta. Today, NiTi research and work on other shape memory alloys is considering long-term biological and chemical stability such as biocompatibility and corrosion resistance / degradation. Long-term corrosion resistance (where long-term equates to life time of the patient) is a critical concern since corrosion could cause toxic effects[o] and may weaken the mechanical properties of the implant.

[n] Shape memory alloys are a certain class of stimuli responsive materials.
[o] Animal testing has identified cytotoxic, carcinogenic and mutagenic effects.

The “true” shape memory effect is limited to metallic alloys due to crystalline structural changes. Nevertheless, a similar materials property has also been observed in polymers and these polymers are called shape memory polymers (SMP). Since there is some controversy about the potential toxic behaviour of NiTi alloy, shape memory polymers might be an alternative implant material and therefore currently receive much attention. However, the principle laws of materials science should be kept in mind when considering potential applications for SMP (see Figure 31). Furthermore, SMP show a completely different shape memory effect compared to shape memory alloys, based on their non-crystalline molecular structure. Depending on whether the environmental temperature is above or below the so-called glass-transition temperature, the materials properties vary between a rubbery state and a hard, brittle state. Some authors mention the recovery strain, which describes the force needed to stimulate the material to undergo transition from its temporary stage back to its permanent stage, as being fairly low compared to SMA[87]. Other researchers do not report such limitations in the materials characteristics of SMP[88]. It should be noted that also polymer processing without additives is complicated and these additives could cause toxic reactions in the body. Some polymers are known to cause thrombogenic reactions, while other polymers could undergo chemical degradation.

A great advantage of SMP is that their properties can be tailored by copolymerisation with other polymers. Furthermore, the mechanical properties of shape-memory alloys (such as Nitinol) can only be varied over a limited range (8% maximum deformation between temporary and permanent shape), while shape memory polymers can be deformed to elongations of up to 1100%. Recently, researchers have developed SMPs that are both biocompatible and biodegradable upon external stimulus. These SMPs have been used in stents, which could be compressed and fed through a tiny hole in the body into a blocked artery. The temperature of body would trigger the polymer's expansion into original shape. Instead of requiring a second surgery for removing the SMPs, the polymer would gradually dissolve in the body over time. In some cases, biodegradable polymers are the only solution in applications such as the reconstruction and functional maintenance of blood vessels.

Figure 31. Mechanical behaviour favours smart alloys and smart polymers for biomedical applications (biocompatibility is another key parameter).

Figure 32. Metal stent covered with a biodegradable polymer, which minimizes the damage and in-growth of tissue (restenosis) (photo with kind permission from Uppsala University).

As already mentioned in the section "*Improvement of Existing Implants and Medical Materials*", surface modification technologies offer a wide variety of opportunities to improve the biocompatibility of implants. At the same time, thin-film deposition technologies, laser treatment, electropolishing and plasma surface treatment can increase the corrosion resistance of such devices. Also, researchers are trying to find anti-adhesive nanocoatings for teeth to reduce plaque formation, which would have a great potential to extend the lifetime of natural teeth[89]. Furthermore, these technologies can be used to realise devices in the emerging field of drug-device combinations. Already available today are steroid-eluting pacing electrodes (which are part of pacemakers and were released already 20 years ago to help reduce scar tissue) as well as drug-eluting stents[86]. An important breakthrough in stent technology has been the addition of a thin coating on the stent wires which contains a small amount of a specific drug. The drug coating is designed to prevent re-narrowing of the coronary artery after stent placement. There are several challenges in this technology, such as to create a coating with the right amount of drug in such a way that the drug is not degenerated. Also the elution profile has to be tailored. Drug therapy with controlled dosing could be used for setting up an in vivo insulin-releasing system. Furthermore, these approaches have to be combined with self-monitoring diagnostic devices and sensors as well as better control of drug release mechanisms. Important approaches for both problems are provided by nanotechnology. For realisation, advances in materials systems for sensors, smart materials for electronics and adaptive polymers are needed. For applications such as neuroprostheses[p], heterogeneous materials and the interfaces have to be investigated and fully understood[90].

Figure 33. A first-generation bionic arm (photo by Dayna Smith, The Washington Post)

To broaden the application of smart materials systems, progress in mass production technologies for such devices is needed, to reduce cost of manufacture and allowing deformation of these often limited ductility materials systems. Some smart materials systems could help in creating assistance devices for the disabled and the elderly. However, communication between researchers and interest groups of disabled

[p] Neuroprosthetics is a discipline related to neuroscience and biomedical engineering concerned with developing neural prostheses, artificial devices to replace or improve the function of an impaired nervous system. The best-known device is the heart pacemaker. Other motor prosthetics are bladder control implants and motor prosthetics for the conscious control of movement. Furthermore, sensory devices such as the bionic ear and bionic eye are under development. Even the replacement of damaged brain regions seems possible in the very far future.

people should be improved. Although disability aspects of materials development have been recorded, it is recognised that there is a great deal of scope for further developments to help the disabled and the ageing population.

Materials Research for Regenerative Medicine

Ground-breaking innovative approaches are needed to especially achieve the mid- and long-term goals in the development of biomaterials for next generation implants; these may be found in the area of nanomedicine[91]. According to the European Technology Platform (ETP) “Nanomedicine”, this research area is defined as the application of nanotechnology to achieve breakthroughs in healthcare.

In the long-term range, researchers are targeting regenerative medicine. Whereas the aim in the development of traditional artificial implants is a high match of the properties of the replaced organ, in regenerative medicine the goal is to induce the re-creation of the organ with identical nanostructure by the body itself. These technologies are expected to enable the replacement of tissue and organs by living and functional replacements. To enable these technologies, materials innovations are needed in biodegradable polymers, rapid prototyping, drug delivery and biomimetics. Bioactivity is the key factor. An artificial matrix that contributes to the technology of regenerative medicine has to be “bioactive” during its early period of contact with the biological environment. One of the key missions in regenerative medicine for materials researchers is to seek for polymers, hydrogels, and other soft materials that can function as bioactive matrices.

Humans who have suffered from strokes or heart attacks face a tremendous deterioration in their quality of life since neurons in the stroke region die and tissue is replaced by scars. Regenerative medicine is a challenge, in which the emerging knowledge in physical sciences (such as biomaterials science, supramolecular chemistry and self-assembly) and life sciences disciplines (such as stem cell biology and system biology) have to be combined with nanotechnology and clinical medicine to learn how to trigger the regeneration of failed human organs and tissues[92]. In regenerative repair of human organs, materials will be transformed from being providers of mostly mechanical functions to sophisticated regulators of biological activity. As mentioned in the previous section on artificial solutions with Smart materials, today, the same metals, ceramics, and polymers used in engineering for technological applications are also being used to replace failed blood vessels, heart valves, keep blood vessels open (metal stents), reconstruct joints with parts fixed to bone (hip and knee replacements) and secure artificial teeth in the jawbone (threaded metal posts)[92].

Figure 34. Successful reconstruction of an ear by tissue engineering[93] using biocompatible fibre material combined with gel as a substrate (Charité Berlin)

The most advanced therapeutic option in regenerative medicine is tissue engineering. Tissue engineering[91] is scaffold-guided tissue regeneration and involves the seeding of porous, biodegradable scaffolds with donor cells, which differentiate and mimic naturally occurring tissues. The materials challenge of generating such scaffolds is discussed in the chapter on "High Tech Textile Materials" on page 101. These tissue-engineered constructs are then implanted into the patient to replace damaged tissues, where they will be resorbed and replaced by host tissues. Therefore the generation of viable blood supplies and nerves is a critical requirement for successful regeneration. Current clinical applications of tissue-engineered constructs include the engineering of skin, cartilage and, in certain examples, bone. Recent advancements include the use of adult stem cells as a source of regenerative cells, and the use of cell-signalling molecules as a source of molecular regeneration messengers.

An important strategy for regenerative medicine is the biomimetic approach which will require both intelligent biomaterials and bioactive signalling molecules. Nanoengineering will enable the creation of biomimetic cellular environments and will induce specific cell responses. The intelligent biomaterials used in regenerative medicine will most likely be resorbable polymers that have been tailored at the molecular level. These intelligent polymers are able the respond to changes in the environment (such as a change of molecular conformation in response to changes in temperature, pH, electrical or physical stimuli; see further information on stimuli-responsive polymers on page 105) and will induce interactions with cells. A challenge in regenerative medicine is to control cell differentiation. Stem and progenitor cells have the ability to differentiate into derivative tissues and have great potential for tissue repair or replacement. Typically, differentiation is controlled by soluble compounds such as growth factors. Recently it has been observed that three-dimensional (3D) macroscopic gel-like solids, consisting of bioactive peptides, are capable of directing differentiation[94]. These highly hydrated 3D gels are formed from peptide amphiphiles, which self-assemble in aqueous media to form nanofibres with diameters of 5 - 8 nm. These gels are able to direct the rapid differentiation of neural progenitors into neurons. Researchers are trying to identify the chemical fundamentals of the interaction mechanisms by screening materials libraries using high-throughput techniques.

Researchers are also developing smart biomaterials that respond to specific cellular signals. Such hydrogel-containing smart biomaterials will be replaced by cells forming tissue[94]. Some of these smart gels also support the infiltration of cells and the formation of mineralised tissue. Implantation is a critical factor in the clinical application of these next-generation biomaterials. In solving this challenge biodegradable shape memory polymers and stimuli-sensitive materials will play an important role. These materials could lead to new forms of minimal invasive surgery.

Regarding biomimetics and self-healing structures, a better understanding of the mechanisms of structures in natural materials with unique properties is needed as well as about the methods to create self-healing structures. Therefore, a new quality of interdisciplinary research combined with an efficient infrastructure would be beneficial. Both research fields are highly complex, so that a virtual network could be a helpful approach. The development of self-healing structures should distinguish between biomaterial (organic) stem cell strategies and inorganic materials such as shape memory alloys, since these are two different approaches. One interesting approach in the area of self-healing structures would be "living polymers" that could be activated on demand. Strong emphasis needs to be placed on biomimetic structural design (evolution has provided the best solutions so far), but there is a lack of realisation of the complexity of this subject area. It is suggested that a network in biomimetics for Europe could provide information and focus on what is especially multidisciplinary research.

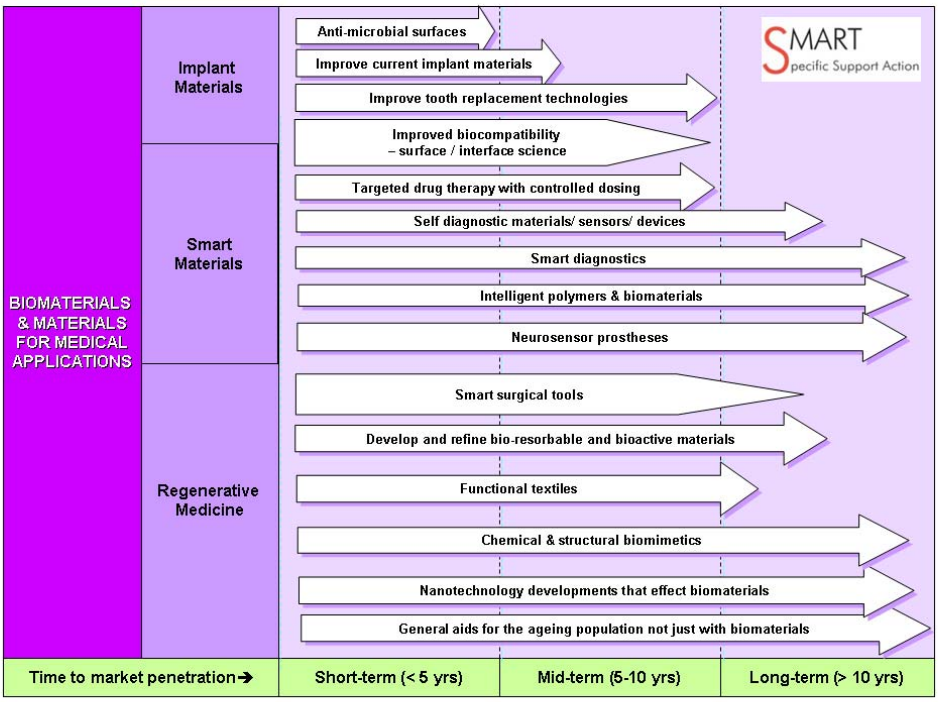

Figure 35. Roadmap "Biomaterials"

In the European White Book on Fundamental Research in Materials Science, Bill Bonfield gave an overview about bone and skeletal implants in a chapter entitled "Biomaterials: Research and Development", before looking at the prospects for tissue engineering. For European research, the following research priorities are mentioned: develop a distinctive materials science approach to embrace the continuum from gene to protein to cell to biomaterial to medical device; emphasise the innovation of novel biomaterials and tissue-engineered artefacts, based on the biological template, for tissue and organ replacement; develop an understanding of the mechanisms controlling the interaction of cells with second-generation biomaterials and third-generation tissue engineering scaffolds; encourage the progression of novel biomaterials from the laboratory to distinctive clinical applications in patients by entrepreneurial technology transfer. These identified priorities are in good agreement with the research needs identified by the SMART project. A detailed work plan and strategy for the development of regenerative medicine can be found in the Strategic Research Agenda for "Nanomedicine"[91].

The identified research SMART priorities in the area of *Biomaterials and Materials for Medical Applications* are as following:

- Surface modification technologies for producing innovative multifunctional coatings on implants;
- New production technologies for smart materials;
- Stimuli-responsive materials (especially Shape Memory Polymers) for smart surgery tools and high-tech artificial implants;
- Materials for adaptive drug-device combinations;
- Fundamental research on heterogeneous materials interfaces for prosthetics to enable disabled citizens a better participation in social life;
- Identification and characterisation of "bioactive" polymers, hydrogels and other soft materials;
- Research on intelligent polymers and biodegradable materials;
- Improved knowledge management in biomimetics;
- Fundamental research on mechanisms-directed differentiation.

Roadmaps: Materials for Packaging

The term “packaging” is used in this chapter in regard to materials setting up a protective barrier for products. Besides this meaning there are also materials for packaging in the sense of the integration of electronic devices, which play an important role for developments in the area of automotive electronics, information and communication technology.

The demands on packaging[95] are for improvements in convenience, safety and error prevention, improved product performance, and easier openability and readability. Novel technologies are under development that will enable safe and sustainable packaging through detectors for oxygen levels, indicators for bacterial toxins and microbial growth, or the integration of time-temperature indicators for detection of improper handling or storage[96].

According to the roadmap, originally derived from the literature screening and modified at the Lisbon workshop, research in materials for packaging can be divided into two major research areas (see Figure 37). The first field are all topics related to the greening of convenience and low-cost packaging materials and the second field concerns materials for intelligent and safe packaging, which will be an added-value to the product.

Greening in Convenient and Low-Cost Packaging Materials

The greening of convenient and low-cost packaging is driven by the reduction of waste. Solutions for a zero waste society are biodegradable materials, innovative interfaces and extending the lifetime and expiration date of products. New efficient barrier solutions are needed. Cost, water sensitivity, opacity and limited mechanical resistance are critical factors in packaging. Another important economic driver in packaging is the increasing cost of crude oil, which in turn has resulted in a higher cost of packaging materials such as polyethylene.

In food packaging, there are a number of societal drivers such as family changes, ageing demographics, support for healthy and safe lifestyles, design for the environment and sustainability with easier recycling. Within the next decades in most industrialised countries there will be a substantial increase in the over-65 population. Elderly people will need easy-to-read labels.

The increased health consciousness of most societies in the industrialised world has resulted in a demand for freshness and improved quality of food. Consumers expect a short time between food production and consumption, whilst the shelf-life should be extended for reasons related to safety. Trends[97] show that consumers expect good product visibility, which is difficult to realise with the metallised coating materials used in packaging technology. Also, some property combinations such as transparency and heat resistance, or transparency and light protection, are almost incompatible. Metals are playing a diminishing role in packaging, since for a growing number of consumers such materials are seen as environmental unfriendly because of the high energy needed for their production. This growing environmental awareness is also a cause for packaging producers to avoid chlorine-containing materials (such as PVC, PVDC) that may lead to the formation of toxic dioxins during waste combustion. Also, there is a trend to convenience packaging with better opening and re-closing functions and the ability for microwave heating. Convenience and growing environmental awareness are also responsible for the trend away from glass packaging towards the increased usage of more and more polymer packaging materials.

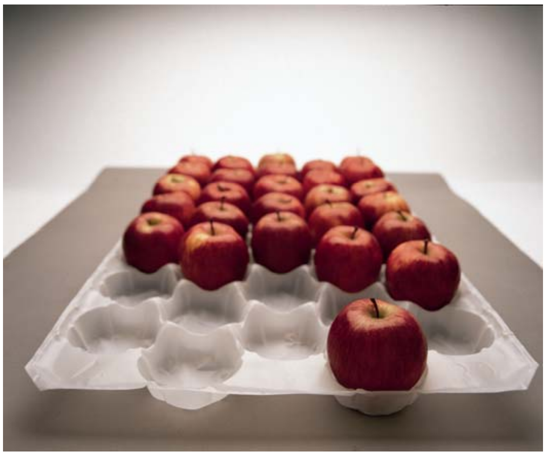

Figure 36. Fruit tray made out of a biodegradable polymer based on maize, potato or wheat starch (photo with kind permission from NOVAMONT)

In today's fast moving world, the time available for food consumption is decreasing and products should be ready to eat, such as by microwave cooking, and, developments such as soups that automatically heat up and drinks that automatically cool down are likely. There are also efforts to enable easier opening of packaged items. Currently the greening of packaging products and the addition of intelligent functionality (see also next chapter) are incompatible developments and will be for some time. However in the very long-term it is likely that materials engineers can develop sustainable materials for both sustainable *and* intelligent packaging concepts.

From the economic point of view a contradictory trend is taking place. Although in packaging production there is a demand for higher processing speeds to increase profits, consumption of packaging material should be reduced for economic and ecological reasons. For example, Nestlé[97] is attributing an average of 17% of the total cost of goods produced to the cost of the packaging. The demand for increased line speeds results in increased loadings on materials, so that the packaging material has to be both thinner *and* stronger at the same time.

One of the most important functions of packaging is to act as a barrier, especially in food packaging. As mentioned above, there is a trend to more plastic-based materials in food packaging and away from metal and glass packaging. The challenge in enabling more applications with plastic-based packaging materials is the improvement of the barrier function. Key parameters for barrier improvements are the oxygen transmission rate and the water vapour transmission rate. Efforts to set up efficient barrier functions can be divided into thin, transparent vacuum-deposited coatings, new barrier polymers as discrete layers, blends of barrier polymers and standard polymers, organic barrier coatings and nanocomposite materials.

In principle, packaging materials can be differentiated between flexible and rigid. In flexible materials the barrier layer traditionally is realised by aluminium layers on a plastic based material. Recently, coatings just a few nanometres thick produced by vacuum-deposition have been introduced. Lamination or co-extrusion with a high barrier polymer is another approach for the realisation of the barrier function in plastic-based packaging (high-barrier polymers: PVDC, EVOH, PVAL, PA; PVAL, EVOH and PA are only good barriers in the dry state and have to sandwiched with a better water barrier). In rigid packaging, the poor barrier function of plastic-based packaging also has to be solved. Therefore a layer approach with co-injection and sandwiching is needed because of water sensitivity. Another approach is blending by mixing with a high-barrier material (high-barrier polymer or inorganic filler).

Thin, glass-like coatings of SiOx have been obtained by PVD since the mid-1980s and by PECVD of gaseous organosilane and oxygen since the early 1990s on PET, PP and PA. Such coated bottles have the advantage of being water-resistant, microwaveable and transparent and they have a very good barrier (comparable to metallised barriers). The problem with such coatings is their limited ductility and crack resistance and their high production costs. Nevertheless, a variety of such products is on the market (Tetrapack bottles, Alcan Packaging, etc.).

In the mid- and long-term, we will move from focussing mainly on the reduction of weight, improvement of barrier functions and substitution of conventional packaging materials by polymers, to a more encompassing approach towards a zero waste society that also considers the efficient usage of resources in natural cycles. Therefore, more and more bio-based materials are being introduced, that will be biodegradable and CO_2-neutral due to their natural origin from renewable resources. As mentioned previously, already today the increasing crude oil price is enabling alternative, bio-based materials to be competitive with petroleum-based products in packaging[98]. A significant breakthrough in packaging occurred in 2004 with the introduction of bottled water in a commercially compostable material. These bottles are made from polylactide, a renewable polymer made from maize (trade name PLA).

Biodegradable polymers are polymeric materials in which at least one step in the degradation process is occurring through metabolism in the presence of naturally occurring organisms[q]. Such biodegradable polymers can be extracted or removed from biomass, such as polysaccharides, proteins, polypeptides or polynucleotides. Also biodegradable polymers such as polylactic acid or bio-polyester can be synthesised from renewable bio-based monomers or a mixture of sources from biomass and petroleum. Finally, biodegradable polymers such as cellulose and polyhydroxybutyrate could be produced by micro-organisms or by genetically modified bacteria[99]. Even though the high oil price is driving developments of bio-based polymers, these materials still have to overcome some bottlenecks. Critical parameters besides cost are performance and processibility. Many of these materials are brittle, have a low heat distortion temperature, high gas and vapour permeability and a poor resistance to protracted processing operations. Their applications are still limited therefore and materials research to improve their properties is needed. Nanotechnological modification of such materials might be a good way to improve their properties for various applications[99]. Investigations have shown that mechanical, thermal and barrier properties can be altered. Most relevant for packaging applications are research studies on biodegradable nanocomposites based on starch and derivates, polylactic acid (PLA), PBS, PHB and PCL. These polymers are mixed with sheet silicates (clay minerals such as kaolinite and montmorillonite) to obtain nanocomposites.

An example of nanocomposite developments are bio-polyesters such as PLA and PHB which have a high potential for packaging applications in many foods and beverages, although their application is still limited due to poor performance. Researchers are trying to improve this performance by adding clay minerals and are therefore using PLA and PHB to form nanocomposites.

[q] Much information about biopolymers is available under: www.biopolymer.net

Materials are not only used for packaging, but are also used to improve the food products themselves[99]. Edible films and coatings are thin, continuous layers of edible material used as a barrier between food components to avoid mass transfer. Such coatings might form an integral part of the food itself and are applied as solutions (paint-brushing, spraying, dipping) or as a molten component. Materials used for such edible films and coatings are water-soluble polysaccharides (cellulose, starch, pectin) or lipids (waxes). Polysaccharides play a tremendous role in the food industry, since they are responsible for adding properties such as crispness, compactness, viscosity and mouth-feel to a food product. Waxes are commonly used for the coatings of fruits and vegetables to retard respiration and lessen moisture loss. Researchers are planning to investigate the opportunities of adding new functions to such edible films by the incorporation of nanoparticles. For example nanoparticles that release antimicrobial agents in a controlled manner could be incorporated.

Furthermore, nanotechnological modifications also offer improvements to pulp, paper and cardboard packaging materials. Recently, a nano-hybrid technology has been applied to paper products that improves gloss and smoothness. A comprehensive overview about ongoing research to obtain sustainable fibre-based packaging materials and the opportunities and risks of applying nanotechnology can be obtained at the website of the EU project “Sustainpack” (www.sustainpack.com). Further information is available on the website of the forest-based sector technology platform and from the EU project “Biorenew”.

Materials for Intelligent and Safe Packaging

Drivers for intelligent and safe packaging are the need for high-added value products of European companies to be internationally competitive, and anti-counterfeiting measures. Also important are logistics, consumer trust of food products and improving the safety of products (particularly for pharmaceutical products).

Looking at the expected developments of packaging materials within the next 15 years, the study “Consumer Packaging: Opportunities for Smart Technologies”[100] states that RFID and printed electronics are the two technologies that will have the greatest impact on packaging. RFID has already started to revolutionise logistics worldwide and applications in textile products and shelf products in supermarkets are the next developments. Smart packaging will help to fight counterfeiting and the piracy of products, to strengthen the loyalty of consumers to brands and to avoid the misuse of products (such as medicinal products). There are visions that printed electronics on packaging will provide screens on products for video clips for marketing, logistics and education. First applications might be flashing messages on products in different colours[101]. Adding such smart functions to packaging might be the marketing tool for the next decade to make products competitive in a global market with equal technical standards. These electronics will be printed onto the paper or plastic packaging. Developments in conducting polymers and printing technologies are needed to realise this vision.

Due to the ageing population and a stretched health service, the importance of delivering the right medication effectively will increase[100]. Smart Materials Packaging remind patients to take their medicine and help them to take the right medicine with the right dosage. Studies have shown that as many as 50% of patients fail to comply with the terms of their prescriptions. Health and economic consequences of non-adherence include increased hospitalisations and home visits, disease progression, complications, premature disability and even death.

Whereas the developments mentioned above will lead towards interactive functions of packaging in the long-term, in the near future we might see active functions such as smart anti-microbial systems and indicators giving the customer information about the quality of the product.

An intelligent packaging concept with an active function is the so-called "bioswitch"[102] concept. The bioswitch reacts on external stimuli due to changing environmental conditions such as pH, temperature, humidity and the presence of metabolites,. , Such an intelligent system can be more specific therefore and will only be activated on demand. An important application of the bioswitch concept is in anti-microbial packaging of food. This packaging material includes a preservative-releasing system, which aims at extending the shelf-life of the packed food. This system only releases its preservative on command, which means that a preservative will be released from the packaging material, to inhibit the growth of the emerging bacteria, only if bacterial growth occurs. The bioswitch system is intelligent because the inhibitor is only released if there is bacterial growth, and levels of antimicrobial agents in the food itself can be reduced. From the materials point of view, the bioswitch concept is realised by particles consisting of an anti-microbial compound which is coated with a natural polymer (such as a polysaccharide). These particles are coated onto the food packaging. In the case of initial microbial contaminations micro-organisms will start to secrete enzymes, which will hydrolyze the polysaccharides of the bioswitch particles. Partial degradation of the natural polymer will induce release of the anti-microbial compound, resulting in the inhibition of microbial growth.

In some European countries, there have been major scandals in the past concerning spoiled food products that have entered the European market. For customers it is often not possible to identify such low-quality products. Intelligent packaging could help indicate freshness and might warn visually if food is no longer safe. Monitoring the quality through time-temperature indicators, gas-leakage indicators, toxin indicators and spoilage or freshness indicators could help improve the trust of European consumers in food products.

As already mentioned, RFID is one tool to fight counterfeiting. Also the development of highly sophisticated inks is an approach to distinguish between the original and the fake product. Recently, QinetiQ developed a key-lock polymer system using interference colours as a security feature. The packaging of the product incorporates the lock polymer, and the interference colour that confirms a genuine product can be obtained only in combination with the key polymer that is held by the customer[100]. Researchers at Toronto University have developed a nano-structured polymer that can be used to record biometric features, such as fingerprints, photos and signatures. This technology can also be used to identify fraud.

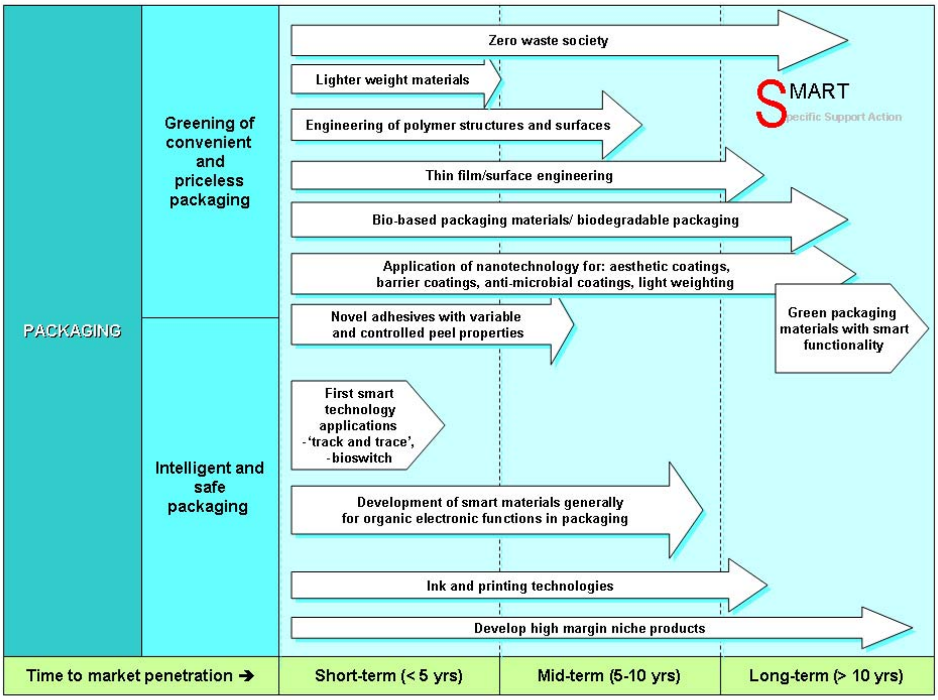

Figure 37. Roadmap "Materials for Packaging"

Limited resources, a changing lifestyle of European citizens in a globalised world, the growing relevance of anti-counterfeiting for European industry and the ageing society are the main drivers for technological innovations in packaging materials. The identified materials research tasks are:

- Nanotechnological improvements of packaging materials
- Improving the materials performance of bio-based polymers
- Intelligent polymers for printed electronics
- Sustainable materials for smart packaging

Roadmaps: Materials for High-Tech Textiles

According to ETP "Textiles", the market share for textiles used for clothing was 41%, for home and interior applications 33% and for technical and industrial applications 26% (2005, EU-25).

To date textiles have been mainly used for clothing and have had only the passive functions of keeping people warm and protected from the elements. Textiles were of cultural importance also, since they were an expression of societal trends in terms of fashion and underlined the belonging to certain groups (uniforms). Because of advances in fibre technology we can expect today, that more and more textiles will have sensing and adaptive functions, so that textiles in clothing could function as a "second skin". Besides innovations in fibre materials, advances in manufacturing technology by intelligent garment manufacturing, automated spherical sewing systems, RFID technology, 3D CAD technology, online-retail and 3D human body scanners all play an important role in the transformation of the traditional textile industry towards a high-tech industry. Textiles also play an important role for house interiors. Even though there are alternative materials, textiles are favoured because of their properties such as flexibility, softness, light weight, durability and easy production in all possible shapes, forms, colours and designs.

Innovations in textile materials can be divided into new garments, technical textiles and fabric-based composites[103]. In the field of new garments, innovations in fibre materials are aiming towards smart textiles and bio-based products. The SMART roadmap for high tech textile materials in Figure 40 has been divided into a "Technical Textile" section and a "Smart Materials" section. Technical textiles are defined as textile products manufactured primarily for their technical performance and functional properties. Their end-uses range from simple products such as dental floss and sutures, to heart valves and vascular prostheses; from air filters to heat and flame barriers; and from car seat covers to load-bearing composite materials[104]. Smart textile related research topics are the use of electronics in fabrics as well as new conductive, electrochromic and luminescent polymers in fibres. In addition, further research is being carried out on chemical sensing and garments that monitor physiological status (i.e. blood pressure). Finally, research is aiming at new developments in chemical and biological protective fabrics, engineering considerations for environmental control within fabrics and new high-strength fibres for protective armour. However, such additional protection often has a negative effect upon the exchange functionality of the human skin; in certain cases this can be severe such as in the case of full body armour, fire-fighter suits, uniforms or diving suits. Functional and even smart or intelligent clothing are the innovative response to such limitations.

Smart Textiles

While all types of clothing have some basic decorative or protective effects, *functional clothing* refers to products in which one or several specific functionalities are emphasised. Smart garments can, for instance, adapt their insulation function according to temperature changes, detect and react to vital signals of the wearer's body, change colour or emit light upon defined stimuli and detect and signal significant changes in the wearer's environment.

An already commercialised example of smart textiles is the integration of wearable computers and wireless communications with textile substrates to produce clothing that can monitor heart and respiration rates as well as body temperature. However, these health monitoring functions as well as today's available protective clothing are still based on incorporating current device technologies onto common fabric substrates. A future goal is to build devices into the fibre itself. Recently Cartysse et. al.[105] reported about the successful testing of textile sensors for the equipment of a wireless monitoring suit for the monitoring of the electrocardiogram (ECG) and respiration rate of children in a hospital environment. This suit is used for long-term monitoring of children and should avoid skin irritation problems and allergies caused by conventional sensor technologies. The sensors, which are entirely fabricated out of textile, are integrated in a prototype belt of the monitoring suit (see **Figure 38**). The complete suit will not contain only the sensors, but also the interface, data handling, storage and transmission electronics. Therefore, distributed, miniaturised circuitry, textile interconnections, a textile antenna and hermetic packaging have been developed. A bottleneck of such smart suits is their durability and washability.

Figure 38. Paediatric application of a wireless monitoring suit (photo with kind permission of K.U. Leuven)

Smart suits will in the future not be limited to medical applications of infants but will also be used to help elderly people, ill persons and disabled people[106].

Further progress in developing smart suits is needed for protecting fire-fighters, law enforcement personnel, medical personnel and peacekeepers when dealing with chemical and biological threats in many environments. Thus, urban, agricultural, and industrial full-barrier protection, such as hazardous materials suits, or permeable adsorptive protective over garments are required[107]. It can be expected that in the future we will see protective smart suits with the capability to selectively block toxic chemicals, to chemically destroy toxic materials that contact the fabric, and to detect hazardous agents on the surface of the fabric. Such smart protective suits with enhanced chemical and biological protection will rely on materials developments such as selectively permeable membranes, reactive nanoparticles (especially nanometal oxides), reactive nanofibres, biocidal fabric treatments and intelligent polymers as well as optical fibres. Selectively permeable membranes can exhibit a high level of water-vapour permeability, but at the same time be resistant to the permeation of organic molecules. These membranes provide protection from hazardous organic chemicals while allowing a mechanism for water vapour transport and evaporation so that the fabric is comfortable to wear.

Optical sensors could be used for internal stress monitoring in textile composites. Such fibre-optic sensors could be woven into the uniforms of law-enforcement personal, in which the sensing function is based on the ability to change the light-propagation properties of optical fibres with various cladding materials. Such next-generation fibre-optic sensors might be even used to warn the wearer of the exposure to biological or chemical agents. A further step in the development of high-tech textiles would be fabrics being adaptive to the environment. Therefore, a shift from electronic-textiles to interactive textiles is needed. Assuming a shift to "i-textiles", the fabric materials will not just be designed to warn the wearer of threats, such as the presence of chemicals or biological contaminants, but also ultimately adapt electronically to protect the wearer.

The protective functionality of fabrics plays a key role in the security applications of textile materials. Such applications are not just aiming at a certain strength of fibres, so that the fabric will be impact resistant (i.e. ballistic protection), but also aim at additional functionalities such as camouflage and protective or sensor clothing. This area has been addressed in the roadmap on page 112 in the topic of smart textiles with tuneable properties. There has also been an interest in developing "chameleon" fibre systems that reversibly change colour and appearance for both commercial and military application. Electrochromism[r] and electroluminescence[s] are two general approaches for achieving controlled colour-changing fibres[108]. Materials development has a key role in both. For the electrochromics approach, reversible switching between redox states is a critical factor, while in the case of electroluminescent materials, a high-efficiency emitter is needed. Integration of such systems with the fibre substrate is complicated and additional developments such as transparent conductive electrodes are required. Further problems in the development of chameleon fibres are lifetime, ionic transport to electrochromic materials, flexibility and strength of the material and environmental stability. A critical step in the development of chameleon fibres is finding the right substrate fibre, which has to be a

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[r] In electrochromism, a reversible and visible change in the absorption and reflection behaviour of a material is observed as a result of electrochemical oxidation or reduction.

[s] Electroluminescence is the principle behind light-emitting diodes, in which a fluorescent material is electrically excited, generating the emission of light as the molecule returns to the ground state.

conductive and flexible material with a high strength. Early materials that have been investigated were wet-spun flexible polyaniline fibres with good electrical conductivity. More recently, the formation of polyaniline hollow-fibre membranes is envisaged.

Breakthroughs in the development of smart textiles are dependant on advances in the research field of intelligent polymers[109]. Intelligent polymers can be divided into stimuli-responsive polymers in general and shape memory polymers as well as piezoelectric polymers in particular.

Stimuli-responsive polymers[t] alter their characteristics in response to changes in their environment. A responsive macromolecule is one that changes its conformation or other properties in a controllable, reproducible and reversible manner in response to an external stimulus (e.g. solvent, pH or temperature). One of their most important applications is in controlled drug-delivery systems. As an example the pH range of fluids in various segments of the gastrointestinal tract may provide the environmental stimuli for responsive drug release. Stimuli-responsive polymers can also find application in intelligent textiles. Thermo-responsive macromolecules could be attached to the nanotube fibres that run along the fabric in the outer part of the cloth. The polymer would shrink when the fibres detect cold conditions from the surrounding environment, keeping the inside layers protected. Some conducting polymers change their resistance in presence of chemical contaminants and could be used therefore as sensors[107]. Thermally induced shape-memory effects can be observed in multiblock copolymers, mainly polyurethanes. The mechanism of the thermally induced shape-memory effect of linear block copolymers is based on the formation of a phase-separated morphology with one phase acting as a molecular switch. Possible applications for shape-memory polymers[u] cover, for example, applications in non-invasive surgery.

The properties of piezoelectric polymers are very different from those of ceramic materials. PVDF [poly(vinylidene fluoride)] and certain copolymers exhibit the best electromechanical performance. Typical applications of the piezoelectric polymers cover sensing and actuating devices in medical instrumentation, robotics, optics,

[t] Shape Memory Polymers are a special type of stimuli responsive polymers.
[u] Further expected SMP applications: self-repairing automobile bodies, smart kitchen utensils, switches for sensors, intelligent packaging, smart tools.

computers and also ultrasonic, underwater and electroacoustic transducers and microphones. Future potential applications of piezoelectric polymers include artificial muscles, bio-inspired robotics, active pump applications, sensors to monitor intracellular conditions and actuators as valves for controlled drug delivery.

Electroactive polymers (EAP) respond to electrical stimulation with a significant change in shape or size. They are lightweight and easy to control. EAP materials can easily be formed in various shapes and their properties can be engineered. Available EAP materials can be divided into two distinct groups. The first group are electronic EAPs (driven by an electric field or Coulomb forces) such as electrostrictive, dielectric, ferroelectric and liquid crystals and the second group are ionic EAPs (involving mobility or diffusion of ions) such as conductive polymers, ionic gels and polymer-carbon nanotube composites. Various applications are being explored in the medical (i.e. for sensor arrays, artificial muscles) and aerospace (i.e. for MEMS) fields and for entertainment and consumer products.

An important pre-requisite for approaching interactive smart textiles is the availability of energy. Therefore energy-interactive textiles have to be developed for energy conversion, storage and energy management[110]. For energy conversion developments are needed in materials research fields such as piezoelectric polymers for mechanical-to-electrical energy conversion, photoadaptive polymers that change their mechanical properties in the presence of electromagnetic radiation, photoelectrical materials (i.e. such materials might be used in fibres of tents for solar cells), as well as chemomechanical fibres and magnetorheological polymers. In many fabric applications of smart textiles, the harvested energy will also have to be stored intermediately before used for the smart application. In energy storage the following materials developments are important: heat-absorbing fabrics (i.e. phase change polymers), electret fibres that can store electrical charges (polyolefin-based fabrics), shape memory polymers (see above) and electroluminescent fibres. For energy management, polymeric fibre materials have to developed that will allow energy (photons, electrons) to be transported from one point to another. Promising materials research areas are optical fibres, bioresponsive polymers, conductive polymers and nanotubes.

Technical Textiles

Microbial attack of textile fibres are a serious problem. The problem with textiles in hygiene and medical applications is that they are an excellent medium for growing microorganisms if there are the right conditions of moisture, nutrients, oxygen levels and appropriate temperatures. Natural fibres are more susceptible to microbial attack than synthetic fibres, which are mostly hydrophobic[111]. The problems of microorganisms in textiles are fabric deterioration (discolour, stains, degradation) and the metabolism of nutrients causing odour and skin irritation. Protein fibres act as nutrient for many types of worms. Cellulose fibres are not a direct nutrient for microorganisms, but some fungi convert cellulose to glucose, which is a good nutrient for microorganisms. Also soil, dust and some textile-finishes act as nutrients.

Polypropylene (PP) is one of the most widely used synthetic fibres in the textile industry, and is cheaper and stronger than most other synthetic fibres[112]. PP is widely used in carpets, automotive interiors, packages, cover stocks, cables and napkins. Also PP is used for sanitary applications such as surgical masks, nappies or diapers, filters, hygienic products, etc. For hygienic and medical applications, PP needs antibacterial activity. The use of certain organic antibacterial agents has been avoided to date, since the safety of some halogen compounds with an aromatic group has become a serious concern. Silver is a very good antibacterial agent because it is non-toxic and is inorganic. Recently researchers developed an organic-inorganic nanocomposite fibre which has a permanent antibacterial effect A nanocomposite fibre of sheath-core type using PP chips and PP/Ag master-batches to give varying concentrations of silver nanoparticles has also been prepared .

The antibacterial property of textiles is an essential feature in fabrics used in prophylaxis, medical treatment and hygiene. A significant part of medical, fibre-based materials are antibacterial textile fabrics which can be obtained by various advanced technologies. The application of new nano-technologies offers the possibilities of producing and implementing such products. Typical antimicrobial agents are heavy metals like mercury, silver, copper and metal salts, azo disperse dyes, ammonium salts, chitosan, magnesium peroxides and triclosan[113].

Many properties of textiles can be altered by nanostructuring of the surfaces of textile fibres. Such nanostructures are usually ultrathin coatings on the surface of the textile fibres, which can be obtained by plasma processes. These plasma coatings can increase hydrophilic properties or can make surfaces hydrophobic and can improve the dyeing behaviour. By using silver-targets in the sputtering process, silver nanoparticles can be deposited on the fibres giving anti-microbial properties[114]. Plasma processes have proven to be successful in shrink-resist treatment of wool with a simultaneously positive effect on dyeing and printing[115, 116]. Highly hydrophobic surfaces are produced, which in contact with water are extremely dust- and dirt-repellent and hence should be also repellent to bacteria and fungi. Even multifunctional textiles can be tailored by adjusting plasma chemistry and plasma physics. Regarding agglomeration of particles, toxicity and mechanical durability processing of nanocoatings by plasma processes is advantageous compared to other coating processes like wet chemical processes (also wastewater is avoided by plasma technology). Recently a German research consortium investigated systematically plasma modified surfaces for technical applications in a project within the German WING materials research funding programme[v, 117]. Uniform thickness coatings were produced that were not compact but had an island structure. While nanocoatings in principle allow the combination of bulk properties with properties of the coating, these island structures offer completely new functions.

Textiles are an essential part of interior design, but they are also the main cause of ignition in house fires. Since textiles are highly inflammable the fires rapidly spread. There is a great interest therefore in drastically reducing the flammability of fabrics. However, since in recent decades environmental issues, toxicology and cost efficiency were the main focus of development, most flame retardant inventions date from the 1960s to the 1980s. In principle flame retardancy can be improved by substitution of frequently used fibre materials with inorganic materials, although materials such as asbestos are not an option. Chemical treatment with a flame retardant chemical is another option, but durability is a problem particularly if the textile is mechanically cleaned. Also chemical modification of the polymer itself is an option, and is currently carried out using organic phosphorous compounds. Finally, it has been found recently that inclusion of functionalised nanoclays in polymers can lower the peak heat release rates[118].

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[v] Funded by German Federal Ministry of Education and Research; FKZ: 03N8022%

Composite materials are a class of multiphase engineering materials in which the phase distribution and geometry has been deliberately tailored to optimise one or more properties[104]. In textile-reinforced composites one phase, the matrix, is reinforced by a textile material. Textiles are increasingly becoming part of the construction of buildings and infrastructure as a consequence of the improved performance characteristics of fibre and textile-based engineered materials in terms of their strength-weight ratio, durability, flexibility, insulating and absorption properties, and fire and heat resistance,. Textile-reinforced composites are in a position to replace more traditional construction materials such as steel and other metals, wood and plastics[121]. Examples of ongoing replacements are light-weight textile roofing, textile-reinforced concrete, fibre- and textile-based bridging cables, erosion and landslide protection systems, textile reinforcement of water management systems, fibre-based pipes and canalisation as well as artificial islands and floating platforms. Besides these ongoing replacements in the construction sector textile-based composites are predicted in the near future to replace many of today's metallic and plastic materials used in the automotive industry, ship building or aeronautics, in the machinery and machine tools industry, in the electronics and medical devices sector. Extensive research is also ongoing to develop cementitious composites reinforced with fabrics out of glass, aramid or carbon[119].

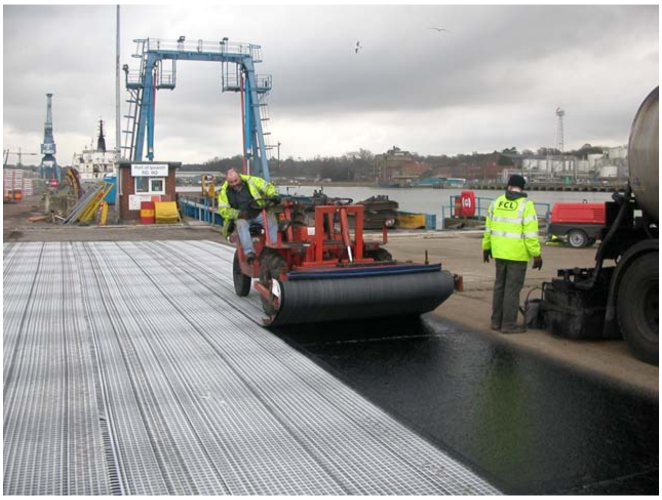

Figure 39: Reinforced asphalt overlay (glass reinforced fibres) at Ipswich Docks, RoRo Ramp, (photo with kind permission from www.asphalt-geotextiles.co.uk)

A trend in the last two decades has been that mankind is not just adapting through nature but also started to change landscapes, so called terraforming. For terraforming geotextiles play an important role. Geotextiles refers to textiles related to earth or soil. This class of textiles can be divided into woven and non-woven types. The woven type has a better strength. Geotextiles can be formed of synthetic fibres, natural fibres or combination of the two. In the past geotextiles were made of natural plant fibres while today are usually formed of synthetic polymers such as polyester, polypropylene (PP) and polyamides (PA). Geotextiles made from natural fibres are less durable as they get decomposed with passage of time[120].

With the inevitable trend towards an ageing society in European and most other industrialised countries, health care and enhancement of quality of life for elderly and (chronically) ill people is becoming a more and more dominant societal priority. Textile products are omnipresent in the field of human hygiene and medical practice. Traditional applications include wound care products, diapers, braces, prostheses and orthoses[w], wipes, breathing masks, bedding and covers, ropes and belts etc. Innovative textile products can both add significantly to effectiveness of medical treatments as well as patient comfort during active medical care or recovery[121]. At the same time, new medical textiles, while not being responsible for a large share of overall health care costs, may contribute to cost containment. Such innovative products: Provide new treatment options (textile based implants instead of scarce donor organs; artificial tissues, joints and ligaments),Speed up recovery after medical treatment (innovative wound dressings; light, breathable orthoses/ prostheses), Enhance quality of life of chronically ill people (functional clothing for people suffering from neurodermitis or psoriasis, anti-dust mite bedding for asthmatics etc.), Facilitate and secure the life of the elderly (adaptive compressing stockings, functional diapers, customised clothing for easy use and functionalities adapted to special needs).

The major requirements from a modern advanced wound dressing are that they should remove excess exudates and toxic components whilst maintaining a high humidity at the wound/dressing interface. They also have to allow gaseous exchange and provide thermal insulation. Furthermore they have to be impermeable to

[w] An orthosis is a device that is applied externally to a part of the body to correct deformity, improve function, or relieve symptoms of a disease by supporting or assisting the musculo-neuro-skeletal system. (source: Wikipedia)

microorganisms and the product has to be free from particulate and toxic wound contaminates as well as removable without causing trauma at a dressing change[104]. Prof. Anand stated at the SMART better life workshop that further improvements in the development of advanced wound dressings are essential.

Recent progress in nanotechnology will have an impact on the development of sterile wound dressings[122]. Textile industry is already an important player in the development and production of nanomaterials, such as fibre containing metal oxide and nanoparticles with *antimicrobial properties.* The advantage of nanomaterials is that beneficial properties can be added to the product without diminishing the aesthetic properties. Also nanotechnology will allow the development of wound dressings, in which the fibres can provide controlled drug release through self regulation. However besides these perspectives the risks of nanoparticles to health and environment have to be considered.

The importance of tissue engineering in regenerative medicine has been already outlined in the biomaterials section of the better life chapter. This technology is a combination of biological and engineering disciplines for the culture of viable human tissues outside the body. Tissue engineering provides surgeons with the possibility of implanting living tissue which will eventually integrate fully with the patients own tissue. A key factor in tissue engineering is scaffolds and this is also the area were textile materials come into play. The scaffold defines the overall size and shape of the implant. Scaffolds also provide the correct internal structure which allows cells to enter the scaffold, attach and grow. The scaffolds are a framework of appropriate surfaces on which the cells will attach onto. Using biocompatible textile materials as scaffolds in tissue engineering has the advantage that the fibres may be bioresorbable so that eventually the entire scaffold is replaced by living tissue. Textiles scaffolds have mechanical properties which provide support to the developing tissue and could give the neo-tissue temporary structural reinforcement.

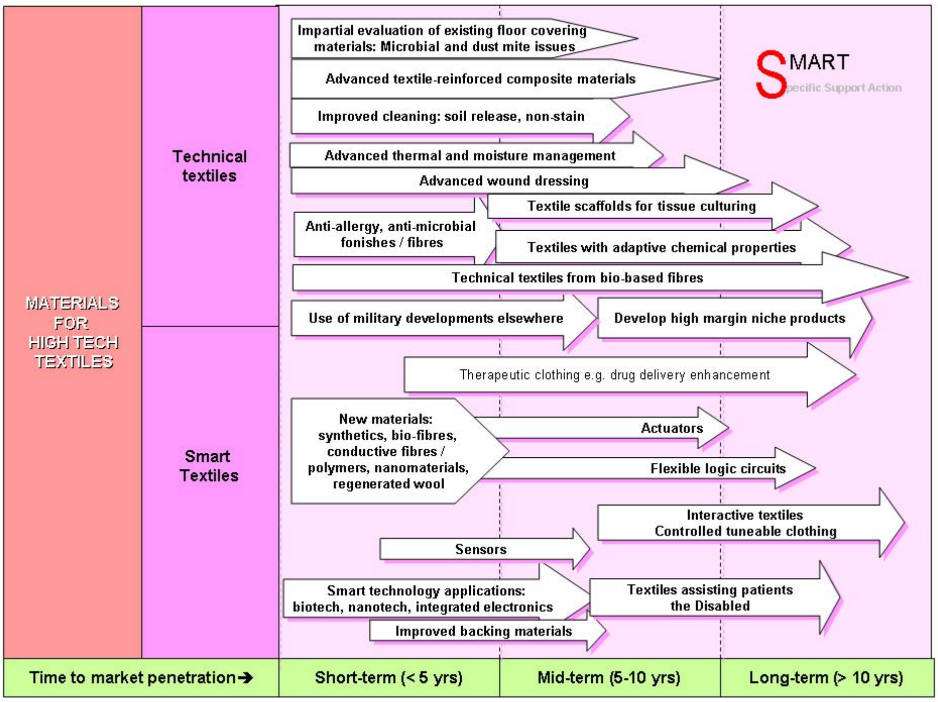

Figure 40: Roadmap "High Tech Textile Materials"

In conclusion it can be seen, that many high tech textile materials breakthroughs might be just around the corner. High tech textiles offer solutions for relevant societal and ecological needs. Smart textiles might offer in the midterm perspective disabled persons and ill people a new quality of life and more privacy. The bottleneck in smart textiles is to produce materials cost efficient and make them sustainable. Technical textiles are an important factor in improving medical healthcare and making medicine in an ageing society affordable. Also technical textiles such as geotextiles will be an important factor in the terraforming to adapt today's landscapes and infrastructures to a changing environment. Therefore materials research priorities in the area of high tech textile materials are:

- Intelligent polymers for smart textiles
- Nanotechnological improvement of technical textiles

Strategies to Maintain Europe´s Position Strong in Materials Technology

Data screening, interviewing and the workshops in the SMART project have shown that Europe has a strong and internationally competitive position in materials research. Bibliometric analyses showed a high output rate of scientific publications. A specific strength of the European materials science community is their research activity in all areas of materials technology. This is due to a portfolio of complementary funding programmes on regional, national and European level. Established and living networks between industry and academia are a great advantage of the European materials innovation system and an important success of European funding as well as federal funding of many European countries. Another reason for the competitiveness of the European materials innovation system is a high grade of internationalisation. The ongoing dialogue concerning technological trends and scientific developments through European Technology Platforms and roadmapping activities provides an important competitive advantage for EU industry

However, even though materials technology is in a good position today, some weaknesses of the European materials innovation system identified in the SMART could develop into a future threat , if no action is taken. While many funding actions have a high visibility on the internet through websites and freely available studies of high quality, the European research has only a weak presence in publication databases, especially in overarching publications such as review papers. In addition the citation rate of most European materials science papers is weak compared to other regions in the world. This leads to the impression amongst experts that research abroad is of higher quality and that there is greater activity. Since this could result in oversees research positions appearing more attractive, ensuring that there is an increased visibility in relevant ranking databases is an important issue to counteract a brain drain. Scientific marketing strategies must therefore be developed. A traditional problem of European materials research is the fact that Europe is excellent in fundamental science but technology transfer rates and time to market have to be improved. The transfer of many industrial R&D activities to low cost regions as well as counterfeiting of innovative developments is a real threat to the European materials innovation system. Also Europe seldom takes leadership in technology transfer processes. Many experts complained about bureaucracy hindering their research progress, or at least slowing progress down. Also researchers were concerned by the absence of predictable long-term funding strategies.

Summarising these critical points, risks for the European materials innovation system are seen in a further brain drain and decreased attractiveness of Europe for foreign excellent scientists arsing from of low visibility of European materials research excellence; a loss of innovative industrial capability by movement of materials R&D to low cost regions; and finally an inefficient return-on-invest of European research funding because of technology transfer weakness and failed counterfeiting strategies. A specific weakness of the European materials innovation system is that there are many different strategic activities for the preparation of roadmaps and the identification of priorities for future funding.

The 7th European Framework Research Programme with a budget of 54 billion € and a duration of seven years is an important step towards predictable long-term developments. Since materials are taking up an adequate part in the 7th FRP in the Specific Programme Cooperation within the topic *Nanoscience Materials and Production*, excellent conditions for a continued successful development of European materials technology are provided. For the first time the European Commission will also support fundamental science in the 7th Framework Programme and have established the so-called European Research Foundation (ERC). The ERC could give excellent researchers a European perspective and therefore help to combat the brain drain of European scientists and also attract foreign researchers.

Recently the European Commission initiated activities to reduce bureaucracy by simplification. Simplification actions have been taken in all political sectors and also in the area of research and innovation. It is still unclear if these steps are adequate to reduce bureaucracy and more effort is still needed. In the area of European materials research funding the Commission introduced a two-stage proposal submission system and reduced the number of funding instruments. This should help to reduce oversubscription and give applicants a clear orientation.

Crucial for the success of the European materials innovation systems are the right decisions about relevant up-coming research topics and actions to improve technology transfer. There are many relevant European foresight activities in materials science. Cooperation between different strategic materials activities, such as European Technology platforms EUMAT, SUSCHEM, Forestry Platform, the Steel platform and materials-relevant ERANETs such as MATERA, Chemistry and ACENET, should be improved to obtain a dialogue process about the future of European materials R&D. First attempts have been made by setting up the network MaterialsEuroRoads, a dialogue platform for materials foresight experts, and the MATERA Outlook Conferences.

A positive development is that the Commission, the federal ministries of European member states and funding agencies are involved in this dialogue, since foresight is only useful if some of the greatest identified potentials will be converted into research projects. Another very crucial question for the future development of the European materials innovation system is how to improve the number of successful technology transfers, reduce their time to market and ensure that legal rights are not violated outside Europe. Many different actions have been started in the past in this area, but so far no silver bullet has been found. Promising approaches are the patent marketing agencies that have been established in the last five years in Germany[123], and the Cordis technology market place[124, 125], wherein using the search term "materials" more than 120 technology offers can be found.

Summary

SMART is a Specific Support Action funded by the European Commission within the 6th Framework Programme in Priority 3 “Nanotechnology and Nanosciences, knowledge based multifunctional materials, new production processes and devices”. The objective of the SMART project is to give the scientific community and the European Commission important information about specific strengths and weaknesses in European materials technology as well as to draw a picture of materials research in the future.

The SMART process was divided into several stages. The first stage involved data screening on the forecast side and identification of relevant studies on the foresight side. In the second stage interviewing of experts and analysis of studies led to further progress. Materials relevant foresight scenarios were used to identify the thematic focus areas for the workshops. In the third and final stage roadmapping exercises were carried out which combined the forecast and foresight results from three thematic workshops.

Bibliometric studies prove that Europe’s position is competitive in all areas of materials science. By analysing the number of publications in different materials research areas per year it was found that Germany, Italy, France and United Kingdom have a high output of scientific materials science publications in all research areas. Poland and Spain have a significant publication number per year in the field of macroscale materials. Spain has also a high output in bio-, smart- and nanomaterials publications. Sweden has a significant activity in modelling. Excellence in materials research was measured through the impact of materials research publications and by surveys taken from materials experts. For example high impact numbers were measured for publications from Germany, Great Britain, Switzerland, the Netherlands, Belgium and France.

The evaluation of recent foresight studies led to the identification of the long-term focus fields of energy/ environment, better life and security.

Energy is a strategic resource for industrialised countries so the development of future energy technology is of great importance for Europe. Energy safety and CO_2-reduction are the main drivers in this field. The research priorities identified are innovative gas separation membranes for CO_2-capture technology, corrosion resistance materials for various energy technologies, advanced materials for future fusion technology, energy storage materials, light-weight materials for energy efficiency and materials for advanced solar cells.

While materials for security applications are not at the forefront of security research, materials research is a technology enabler in the area of sensors and scanners, and at the same time could be an important factor in making these technologies widely available. Smart materials, polymers and nanomaterials are beginning to revolutionise security technology in the areas of protection by innovative armour and in the field of anti-counterfeiting.

The identified research SMART priorities in the area of biomaterials and materials for medical applications are surface modification technologies for producing innovative multifunctional coatings on implants, stimuli-responsive materials for smart surgery tools and high-tech artificial implants. Research on intelligent polymers and biodegradable materials is a top priority.

Limited resources, a changing lifestyle of European citizens in a globalised world, the growing importance of anti-counterfeiting to European industry, and the ageing society are the main drivers for technological innovations in packaging materials. Nanomaterials, intelligent polymers and bio-based polymers will play a key role for innovations in packaging.

Finally, in the area of high-tech textile materials, intelligent polymers for smart textiles and nanotechnological improvement of technical textiles are important innovations for transforming this traditional industry into a high-tech sector with a secure and growing European future.

Materials innovations are an important enabler for anticipated future scenarios. The 7^{th} European Framework Programme is a great opportunity to further strengthen the competitive role of Europe in materials technology. Visibility of excellent activities, technology transfer and strategies for brain-gain will be crucial points for success. Platforms such as EUMAT, SusChem and MaterialsEuroRoads together with the ERANET on Materials will be forums for further strategic development and, at the same time, tools for implementation.

Index of Figures & Tables

Index

References

[1] Martin Möhrle, Ralf Isenmann, Technologie Roadmapping, Zukunftsstrategien für Technologieunternehmen, 2. Auflage, Springer 2005.

[2] Dirk Holtmannspötter, Sylvie Rijkers-Defrasne, Christoph Glauner, Sabine Korte, Axel Zweck, Aktuelle Technologieprognosen im internationalen Vergleich, Zukünftige Technologien Nr. 58, Düsseldorf, Juni 2006

[3] Loew, H.-C. (2003). Frühwarnung, Früherkennung, Frühaufklärung: Entwicklungsgeschichte und theoretische Grundlagen. Frühwarnsysteme. R. Schatz. Fribourg, InnovatioVerlag**:** 19-47.

[4] CARS 21, a competitive automotive regulatory system for the 21st century, EU COM 2006, final report.

[5] European Commission 2002

[6] www.CEFIC.org

[7] www.eicta.org

[8] Isak Karabegović, Darko Ujević, Applying Intelligent Systems as a Basis for Improving the Position and Competitiveness of the European Textile Industry, FIBRES & TEXTILES in Eastern Europe January / March 2006, Vol. 14, No. 1 (55)

[9] http://www.in-cites.com/institutions/mat-sci_1996-2006.html

[10] Anthony van Raan and Thed van Leeuwen, CWTS, 2001 (www.cwts.leidenuniv.nl).

[11] Globalization of Materials R&D, National Research Council, The National Academies Press, Washington, 2005 (http://www.nap.edu/catatlog/11395.html)

[12] http://cordis.europa.eu/foresight/definition.htm

[13] Source: Handelsblatt, 20th of March 2007.

[14] A Technology Roadmap for Generation IV Nuclear Energy Systems, December 2002, http://nuclear.energy.gov/genIV/neGenIV2.html.

[15] Energies for future centuries, J. Ongena, G. van Oost.

[16] Information, fusion, European fusion development agreement, March 2002, www.efda.org.

[17] MIT Study: "The Future of Coal", 2007, http://web.mit.edu/coal/.

[18] Professor Lorenz Singheiser, Director of the Institute for Materials and Processes in Energy Systems, at the Forschungszentrum Jülich in Germany, presentation ate te roadmapping workshop "materials powering Europe"; April 2006, London, UK.

[19] Broschure of German Ministry of Economics, Turbomaschinen, December 2006, www.bmwi.de.

[20] Information from Schlumberger, www.seed.slb.com

[21] Kranzmann, Hünert, Technologien für den Klimaschutz únd ihre Anforderungen an Werkstoffe, Chemie Ingenieur Technik, 2006, 78, No. 12.

[22] Capacity Building for the Deployment of CO_2 Capture and Storage (CCS), UNFCC Meetings, Bonn, presentation of Bill Reynen, 20 May 2006.

[23] A study by the German Physical Society, Climate Protection and Energy Supply 1990 – 2020, September 2005.

[24] Kilner presentation at "Materials Powering Europe" workshop, London, UK, 2006.

[25] R. Stanley Williams, The Evolution of Technology for Electronic Materials over the Last 50 Years, JOM, February 2007.

[26] Direan Apelian, Looking Beyond the last 50 Years: The Future of Materials Science and Engineering, JOM February 2007.

[27] www.fz-juelich.de/ptj/nanomobil

[28] Vineet Veer Tyagi, D. Buddhi: PCM thermal storage in buildings, Renewable and sustainable energy reviews, 11, 2007, 1146-1166.

[29] Photo taken at Hannover Fair 2007: technical data: Loremo GS (GT), less than 11k€ (15k€), 20 HP (50 HP), max speed: 160 km/h (220 km/h).

[30] Strategic Research Agenda for Europe´s Electricity Networks of the Future. European Technology Platform SmartGrids, 2007, EUR 22580.

[31] Power-Cables in the 21st Century, T.J. Hammons, Electric Power Components and Systems, 31, 967-994.

[32] K. Kishio, JSAP International, No. 6, July 2002.

[33] Information on the webpage of the Consortium of European Companies Determined to the Use of Superconductivity (Conectus).

[34] Handelsblatt, January 2007.

[35] Physics News 744, September 6, 2005

[36] R. E. Smalley: Future Global Energy Prosperity: The TeraWatt Challenge; MRS Bulletin, 2005.

[37] Kilner, Presentation at SMART workshop Materials powering Europe.

[38] I. Gurrappa, A. Rao, Thermal Barrier Coatings for enhanced efficiency of gas turbine engines, Surface Coatings and Technology, 201, 2006, pp 3016

[39] L. Singheiser, Research Center Juelich, SMART Presentation at Materials Powering Europe Workshop

[40] L. Singheiser, Research Center Juelich, SMART Presentation at Materials Powering Europe Workshop

[41] Gil, Shemet, Quadakkers, Singheiser et al., Effect of surface condition on the oxidation behaviour of MCrAlY coatings, Surface and Coatings Technology, Vol. 201, Issue 7, 2006, pp 3824.

[42] Ulrich Brill, Hochtemperaturwerkstoffe in der Prozesstechnik, Konstruktion, 5- 2003.

[43] D. Oertel, T. Fleischer; Fuel Cells; Impact and Consequences of fuel cells technology on sustainable development; Institute for Prospective Technological Studies; March 2003, EUR 20681 EN.

[44] European Hydrogen and Fuel Cell technology Platform, "Implementation Plan – Status 2006", www.HFpeurope.org

[45] An overview of advanced materials for hydrogen storage, Elena David, Journal of Materials Processing Technology, 162-163, 2005, 169-177.

[46] Adressing Grand Energy Challenges through Advanced Materials, M.S. Dresselhaus, G.W. Crabtree, M.V. Buchanan, MRS Bulletin, Vol. 30, July 2005.

[47] www.greencarcongress.com/2005/11/new_rigid_polym.html

[48] Dr David Gooch gave a presentation on *Materials Issues in Renewable Energy Power Plants*

[49] Fraunhofer CWMT, Technische Zuverlässigkeit durch vereinte Kompetenz, broschure.

[50] European wind energy at the dawn of the 21st century, European Commission, 2005, EUR 21351.
[51] Renewable Energy Newsletter, European Commission, May 2006, Issue 5.
[52] Danish wind industry association, www.windpower.org.
[53] The wind energy goes offshore, presentation from Fraunhofer CWMT, 2006.
[54] American Wind Energy Association, Wind Energy Basics, February 2007.
[55] Energy Science: Principles, Technologies and Impacts, John Andrews & Nick Jelley, ISBN-10: 0-19-928112-2.
[56] Municipal Solid Waste and its role in Sustainability, IEA Bioenergy, 2003, www.ieabioenergy.com
[57] Biomass, Green Energy for Europe, 2005, EUR 21350.
[58] http://www.esi2.us.es/~rubio/proyec_i.html
[59] Presentation from Dr. David Gooch "*Materials Issues in Renewable Energy Power Plants"* at the SMART workshop Materials for a Better Life.
[60] Einblicke Nr. 40, Universität Oldenburg, Herbst 2004.
[61] Photovoltaic and photoelectrochemical conversion of solar energy, Phil. Trans R. Soc., 2007, 365, 993-1005.
[62] Website of the Institute of Science in Society.
[63] MRS-Bulletin, Organic-based photovoltaics: Towards low cost power generation, Volume 30, January 2005.
[64] Toni Marechaux, Better Materials Can Reduce the Threat from Terrorism, JOM, December 2001.
[65] Electronic olfactory systems based on metal oxide semiconductor sensor arrays, Matteo Pardo and Giorgio Sberveglieri, MRS Bulletin, October 2004.
[66] Presentation of Stefan Kaskel (University of Dresden) at the SMART workshop "Materials for Safe Europe" in Munich in October of 2006.
[67] J. G. Reynolds, B. R. Hart, Nanomaterials and their Application to Defense and Homeland Security, JOM, January 2004, page 36-39.
[68] An optoelectronic nose: "Seeing" Smells by Means of Colorimetric Sensor Arrays, Kenneth S. Suslick, MRS Bulletin, October 2004.
[69] John F Federici, Brian Schulkin, Feng Huang, Dale Gary, Robert Barat, Filipe Oliveira and David Zimdars, THz imaging and sensing for security applications—explosives, weapons and drugs, Semicond. Sci. Technol. **20** (2005) S266–S280
[70] Materials for terahertz science and technology, BRADLEY FERGUSON AND XI-CHENG ZHANG, nature materials **|** VOL 1 **|** SEPTEMBER 2002.
[71] Presentation of Mark Benecke at the SMART workshop "Materials for Safe Europe" in Munich in October of 2006: http://www.benecke.com/
[72] DNA typing in forensic medicine and in criminal investigations: a current survey, Naturwissenschaften 84, 181–188 (1997)
[73] Dusan Gallusek, Materials for a Safe Europe, 2006.
[74] Strategic Research Agenda of the European Construction Sector, December 2005, www.ectp.org.
[75] V. M. Karbhari, F. Seible, Fiber Reinforced Composites – Advanced Materials for the Renewal of Civil Infrastructure, Vol7, No. 2-3, 2000.

[76] C. M. Pastore, Opportunities and Challenges for the Textile Reinforced Composites, Vol. 36, No. 2, 2000.

[77] Doetze J. Sikkema, Maurits G. Northolt, and Behnam Pourdeyhimi, Assessment of New High-Performance Fibers for Advanced Applications, MRS BULLETIN/AUGUST 2003

[78] Krell A., Strassburger E., Ballistic Strength of Opaque and Transparent Armor, *Am.Ceram.Soc.Bull.*, 86 [4] (2007)

[79] N. Wagner, Liquid Body Amor, *Am.Ceram.Soc.Bull.*, 86 [3] (2007)

[80] S.G. Wax, G.M. Fischer, and R.R. Sands, The Past, Present, and Future of DARPA's Investment Strategy in Smart Materials, JOM, December 2003.

[81] Ari Juels, RFID Security and Privacy, IEEE JOURNAL ON SELECTED AREAS IN COMMUNICATIONS, VOL. 24, NO. 2, FEBRUARY 2006.

[82] www.iom3.org/foresight/Smart%20materials%20web.pdf

[83] www.suschem.org/media.php?mId=2678

[84] Ratner, Bryant

[85] Dr. Christian Oehr, Fraunhofer IGB, Stuttgart, presentation at the workshop "Materials for a better life", October 2006, Lisbon.

[86] Innovations in Biomaterials: Achievements and Opportunities Rebecca M. Bergman, MRS BULLETIN • VOLUME 30 • JULY 2005.

[87] Shape Memory Materials for Biomedical Applications, Fatiha El Feninat, Gaetan Laroche,Michel Fiset, andDiego Mantovani, ADVANCED ENGINEERING MATERIALS 2002, 4, No. 3, pp 91.

[88] Shape-Memory Polymers, Andreas Lendlein* and Steffen Kelch, Angew. Chem. Int. Ed. 2002, 41, pages 2034 to 2057.

[89] German Project ZOVAN, financed by the WING funding programme of the German Federal of Education and Research (BMBF), further information available at: broschure "Hochleistungsschichten im Werkstoffprogramm des BMBF – Trends und Potentiale", published by Madeleine Dietrich, PTJ (www.werkstoffinnovationen.de), page 34.

[90] Materials Science and Technology: Challenges for the Chemical Sciences in the 21st Century, ISBN: 0-309-08512-8, 98 pages, 6 x 9, (2003), http://www.nap.edu/catalog/10694.html

[91] SRA Nanomedicine, 2006.

[92] Samuel I. Stupp, Biomaterials for regenerative medicine, MRS Bulletin, Vol. 30, July 2005

[93] Broschure "Regenerative Medizin" of the Federal Ministry of Education and Research www.bmbf.de/pub/regenerative_medizin_biologie.pdf.

[94] Smart Biomaterials, Daniel G. Anderson, Jason A. Burdick, Robert Langer, SCIENCE VOL 305 24 SEPTEMBER 2004.

[95] Dr. Paul Butler, presentation at the workshop "Materials for a better life", October 2006, Lisbon.

[96] Microbial Control by Packaging: A Review, Catherine Nettles Cutter, *Critical Reviews in Food Science and Nutrition,* 42(2):151–161 (2002).

[97] J. Lange, Y. Wyser, Packaging and Technology Science, Vol. 16, No. 4, 2003

[98] S.J. Eilert, New packaging technologies for the 21st century, Meat Science, 71, 2005, 122-127.

[99] Andrea, Sorrentino, Giuliana Gorrasi, Vittoria Vitorria, Potential perspectives of bio-nanocomposites for food packaging, Trends in Food Science & Technology, 18, 2007, 84-95.

[100] Smart.mat, Materials Knowledge Transfer Network, Consumer Packaging: Opportunities for Smart Technologies, Paul LeGood and Wavell Coulson, February 2007.

[101] Electrochromic conducting polymers and packaging products: Polymer selection and methods of application, Priya Subramanian, Noel B. Clark, Richard J.N. Helmer, Joseph N. Barisci, Byung Chul Kim, Gordon Wallace, Leone Spiccia, Douglas MacFarlane, Appita Journal, Vol 59, No. 6.

[102] A, R, DE JONG, H. BOUMANS, T. SLAGHEK, J. VAN VEEN, R. RIJK, VAN ZANDVOORT, Active and intelligent packaging for food: Is it the future?, *Food Additives and Contaminants,* October 2005; 22(10): 975-979.

[103] Advanced Fabrics, Heidi L. Schreuder-Gibson and Mary Lynn Realff, Guest Editors, MRS BULLETIN/AUGUST 2003.

[104] Prof. Anand (University of Bolton), “Technical Textiles their social and economic impact”, presentation at Better Life Workshop, 2006 Lisbon.

[105] M. Catrysse, R. Puers, C. Hertleer, L. Van Langenhove, H. van Egmond, D. Matthys, Towards the integration of textile sensors in a wireless monitoring suit, Sensors and Actuators A 114 (2004) 302–311.

[106] Sungmee Park and Sundaresan Jayaraman, Smart Textiles: Wearable Electronic Systems, MRS BULLETIN/ AUGUST 2003.

[107] Heidi L. Schreuder-Gibson, Quoc Truong, John E.Walker, Jeffery R.Owens, Joseph D.Wander, and Wayne E. Jones Jr., Biological Protection and Detection in Fabrics for Protective Clothing, MRS BULLETIN/AUGUST 2003.

[108] Progress toward Dynamic Color-Responsive “Chameleon” Fiber Systems
Stephen S. Hardaker and Richard V. Gregory, MRS BULLETIN/AUGUST 2003.

[109] Anna Boczkowska, Marcin Leonowicz, “Intelligent Materials for Intelligent Textiles”, FIBRES & TEXTILES in Eastern Europe January / December 2006, Vol. 14, No. 5 (59)

[110] Concepts for Energy-Interactive Textiles, Yong K. Kim and Armand F. Lewis, MRS BULLETIN/ AUGUST 2003.

[111] R. Purwar, M. Joshi, Recent developments in antimicrobial finishing of textiles a review, AATCC Review, March 2004.

[112] SANG YOUNG YEO, HOON JOO LEE, SUNG HOON JEONG, Preparation of nanocomposite fibers for permanent antibacterial effect, JOURNAL OF MATERIALS SCIENCE 38 (2003) 2143 – 2147.

[113] Bogna Goetzendorf-Grabowska, Halina Królikowska, Mariusz Gadzinowski, Polymer Microspheres as Carriers of Antibacterial Properties of Textiles: A Preliminary Study; FIBRES & TEXTILES in Eastern Europe October / December 2004, Vol. 12, No. 4 (48)

[114] Nanostructured plasma coatings to obtain multifunctional textile surfaces, Dirk Hegemann, M. M. Hossain et al., Progress in organic coatings, 58, 2007, 237 – 240.

[115] Plasma treatment of textile fibers, Hartwig Höcker, *Pure Appl. Chem.*, Vol. 74, No. 3, pp. 423–427, 2002.

[116] Textile Plasma Treatment Review – Natural Polymer-based Textiles, Ji-Yun Kang, Maijid Sarmadi, AATCC Review, October 2004, pages 28-32.

[117] Charakterisierung von plasmafunktionalisierten Oberflächen mittels ToF-SIMS und multivariaten Analysemethoden, Marc von Gradowski, Dissertation, 2006: http://ubm.opus.hbz-nrw.de/volltexte/2007/1292/pdf/diss.pdf

[118] Development in flame retardant textiles – a review, A. R. Horrocks, B. Kandola, P. Davies, S. Zhang, S. Padbury, Polymer Degradation and Stability, 88, 2005, 3-12.

[119] Textile reinforced concrete (TRC), Wolfgang Brameshuber, Materials and Structures 2006, 739-740.

[120] www.fibre2fashion.com

[121] "The future is textiles", ETP for the future of textiles and clothing, Strategic Research Agenda, EURATEX, June 2006.

[122] Potential advantages and risks of nanotechnology for textiles by David Karst & Yiqi Yang, AATCC review, March 2006.

[123] www.technologieallianz.de/

[124] http://cordis.europa.eu/aoi/home.cfm

[125] http://cordis.europa.eu/marketplace/home.html

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