SusChem
European Technology Platform For
SUSTAINABLE CHEMISTRY

Innovating for a Better Future

Sustainable Chemistry Strategic Research Agenda 2005

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Foreword

The European Technology Platform (ETP) for Sustainable Chemistry (SusChem) was initiated jointly by Cefic and EuropaBio in 2004 to help foster and focus European research in chemistry, chemical engineering and industrial biotechnology. The SusChem vision, which was published in March 2005, foresees a sustainable European chemical industry with enhanced global competitiveness, providing solutions to critical societal demands and powered by a world-leading technological innovative drive.

SusChem unites a wide variety of stakeholders around this common vision thereby mobilising the necessary critical mass of research and innovation effort. SusChem is an open grouping of stakeholders: new stakeholders interested in chemistry, industrial biotechnology and chemical engineering research, development and innovation can join at any time.

This document represents the current Strategic Research Agenda (SRA) of SusChem looking forward to 2025. It identifies strategically important issues with high societal relevance in the areas of chemistry and industrial biotechnology, determines the challenges in these areas, and defines R&D priorities, timeframes and budgets. Achieving Europe's future growth, competitiveness and sustainable development objectives is dependent upon major research and technological advances in the areas defined by this Strategic Research Agenda in the medium- to long-term. The SusChem Research Agenda offers a unique opportunity to focus the European (EU and national) spending in chemistry-based R&D towards the most promising areas in respect of their impact on these overall goals.

The Strategic Research Agenda has been developed by three individual technology working groups looking at Materials Technology, Reaction and Process Design, and Industrial Biotechnology, and by a fourth working group concentrating on Horizontal Issues that have direct relevance to the activities of all three individual technology working groups. This work was overseen by a Board of high-level representatives from industry and academia. In this context, I would like to thank both my predecessors as chairmen of the SusChem Board, Jan Dopper and Emmo Meijer, for their commitment and contributions.

Additional contributions have been made by an Industry Steering Group, a Member States Mirror Group representing the national research authorities, and a large number of external experts contributing to the SRA via a European-wide consultation process.

It is now up to the European Commission, Member States, industry and academia to implement this Strategic Research Agenda. Further discussion and consultations in the coming months will lead to a detailed implementation plan for this agenda covering the above stakeholders and all other possible contributors.

SusChem is a unique opportunity for the chemical and biotechnology communities in Europe to focus on their strengths and demonstrate their contributions to society. Fulfilling these expectations requires a high level of commitment from both public bodies and private enterprises.

Alfred Oberholz
Chairman SusChem Board
Member of the Board of Management, Degussa AG

Executive Summary

The European Technology Platform for Sustainable Chemistry has prepared a Strategic Research Agenda which outlines the future priorities for European research efforts as perceived by its stakeholders. The document comprises the contributions from four working groups, tasked with identifying key areas of research, the limitations and hurdles faced by researchers, and to propose amendments where necessary for future activities. This process was conducted in an open and transparent fashion, with participants from all spheres of society, from non-governmental agencies through academics to the industry representatives.

The SRA document is structured in such a manner so as to address all aspects of research within the European Union. The SusChem vision is discussed, followed by the economic and social importance of the chemical industry in Europe, the structure of SusChem, the synergies with other European Technology Platforms (ETPs) and the thematic priorities of the 7th Framework Programme for Research and Technological Development. This is followed by an examination of the societal needs that are the driving force behind the activities of SusChem. Three truly visionary projects are described and give an impression of what will be possible in the future using the results of SusChem's proposed research. A budget to realise the goals and targets set by the working groups in the SRA document have also been developed.

The main part of the document is devoted to the contributions from the specific working groups: industrial biotechnology, material technologies, reaction and process design and horizontal issues. To present the reader with an accessible document, the detailed technical discussions have been prepared in the form of an appendix. One point is clear throughout: chemistry is a key driver for innovation in many technologies and disciplines, providing the knowledge to improve and combine the benefits of traditional technologies with nano- and biotechnologies, leading to new and improved products. A clear interdisciplinary approach of the three technology areas, supported by the horizontal measures, is needed for a successful implementation of these challenges.

The *Industrial Biotechnology* section details the approach to make Europe's industries leaders in biotechnology processes and technologies for various sectors, including chemicals, food and nutrition, textiles, leather, animal feed, pulp and paper, energy and waste processing. Industrial biotechnology plays a significant role in increasing the sustainability of the European economy. From a business perspective, the main objectives for R&D in industrial biotechnology are the development and production of novel, innovative products and processes in a cost- and eco-efficient manner, preferentially using renewable raw materials, and the discovery and optimisation of microorganism strains and biocatalysts.

The *Materials Technology* section focuses on materials for mankind's future surroundings, which will be designed to enhance the quality of life. These materials will make life simpler, safer, better and, more importantly, place mankind at the centre of technology. One important factor will be the role of nanoscience and the related nanotechnologies, in providing the knowledge necessary to lead to new innovative products and process methods. Nanotechnology is presented as an important enabling technology for the development of new material technologies.

The *Reaction and Process Design* section considers the developments necessary to achieve sustainable development: the identification, design and development of appropriate products and the processes that will produce them. These fundamental enabling technologies contribute to the entire lifecycle of processes ranging from product development via catalyst and process development, plant development and operation to product handling and logistics. By integrating the complementary approaches of chemical synthesis and process design and engineering, and providing key contributions to all relevant steps from reaction to viability of process plants, they can be applied to all areas of chemistry and biotechnology.

The *Horizontal Issues* section examines the necessary political, social and structural reforms needed to give Europe the required boost to maintain its edge within the increasingly global world of innovation. The focus is to find better solutions for these innovations, thus providing improved security for our society. The top level goal is to ensure that the citizens of the EU benefit from the development and use of innovations based on the SusChem SRA. In particular, there is a need to ensure that SusChem technologies lead to wealth and job creation within the EU. Priority areas for further work within the horizontal arena fit into two themes: *addressing societal concerns* associated with new products and processes; and stimulating *support for innovation*. These include the evaluation and improvement of funding models for innovation as well as means to develop the appropriate skills sets to enhance the human capacity that will underpin these innovations.

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Appendix

Note: The Appendix is available as a PDF document at www.suschem.org

Chemistry has a clear role in delivering technological solutions to the challenges facing society today. It will be at the heart of stimulating the European economy, providing new opportunities and wealth creation that will benefit all citizens.

Introduction

1 Vision

Societal chemistry

Everything that we see, smell, touch or taste is chemical. We are part of a complex chemical and physical system that forms the environment and society in which we exist.

Creative chemistry helps to feed us, clothe us, house us, entertain us and keep us healthy. It provides us with energy and transport, and continues to do all these things whilst advances in chemistry and biochemistry are helping us in conserving scarce resources and protecting the natural environment.

But the best chemistry is yet to come: novel anti-cancer, anti-aging and disease prevention therapies based on exploitation of the human genome; cleaner and more sustainable energy production, storage and supply; reliable and fast high-capacity information storage, distribution and processing; increased food quality and production with less demand on arable land. Chemistry will provide functional materials that will make our vehicles lighter and stronger and, hence, safer and more energy efficient, and make our buildings safer with lower energy consumption thus reducing greenhouse gas emissions. True sustainable development requires increasingly the eco-efficient processes and products that chemistry will provide.

Chemistry in Europe

The SusChem vision responded to the societal needs for chemistry in Europe by:

- **Providing the innovative drive for Europe:** chemistry does not just deliver raw materials - it is a major source of innovation in areas from clothing to energy, electronics and pharmaceuticals.
- **Being at the heart of the new technologies that are the basis of the knowledge-based economy:** chemistry is the core science of nanotechnology, biotechnology and environmental technology.
- **Investing for sustainable development:** chemistry is improving the eco-efficiency of products and processes to optimise the use of resources and minimise waste and environmental impact.
- **Protecting and extending employment, expertise and quality of life:** chemistry is providing the innovation for knowledge-based enterprise across Europe, it is already a knowledge-led sector with a highly trained workforce – it can stimulate significant growth and wealth creation across Europe.

Chemistry provides solutions

Chemistry has a clear role in providing technological solutions to the challenges facing society today and, by building on Europe's strengths, will be at the heart of stimulating the European economy - providing new opportunities and wealth creation that will benefit all citizens.

To ensure the continued intellectual and entrepreneurial success enjoyed by Europe in chemistry, investment is needed in research and innovation, and a business and regulatory framework that protects society and at the same time promotes enterprise needs to be provided.

2 The Chemical Industry in the European Society

The chemical industry

The importance of the chemical industry to the prosperity of the European Union can be illustrated by a couple of simple facts[1].

With chemicals sales of €580 billion out of an estimated world market of €1,736 billion in 2004, the EU(25) is the leading chemical production area in the world. The contribution of the chemical industry to the Gross Domestic Product (GDP) of the European Union is around 2.4%, almost equivalent to the contribution provided by the agricultural sector (2004, Figure 1.1). The chemical industry is a net exporter of goods. The biggest contributors to the GDP are Germany, France, Italy, United Kingdom, Belgium, Spain, The Netherlands and Ireland. In Europe, the chemical industry and the pharmaceutical sector taken separately produce the largest added value per employee of any manufacturing sector (see Figure 1.2).

The chemical industry employs around two million workers in the various Member States. The chemical industry (excluding pharmaceutical companies) comprises about 27,000 enterprises, 98% of which have fewer than 500 employees and can be considered as small and medium-sized enterprises (SMEs). These SMEs account for 48% of sales and provide 51% of the employment. Only 2% of the chemical enterprises employ more than 500 employees, but they generate 52% of the total chemicals sales.

The European chemical industry's energy consumption in 2002 totalled 79 million tonnes of oil equivalents (Mtoe), primarily from gaseous and electric sources. Additionally, 77 Mtoe of fuels (oil, natural gas, etc.) were used as feedstock. Its performance with respect to the environment and sustainable development is quite remarkable: in 2002 the production in the EU(15) chemical industry had risen by 38% since 1990, but total energy consumption had increased by only 2.5% and CO_2 emissions had fallen by 8%. Consequently, CO_2 emissions per unit energy consumed had been dramatically reduced, and the CO_2 emissions per unit of production had been decreased by almost 44% since 1990.

Figure 1.1: EU(25) Gross domestic product by sector.

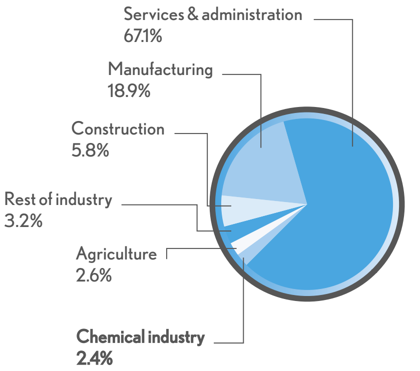
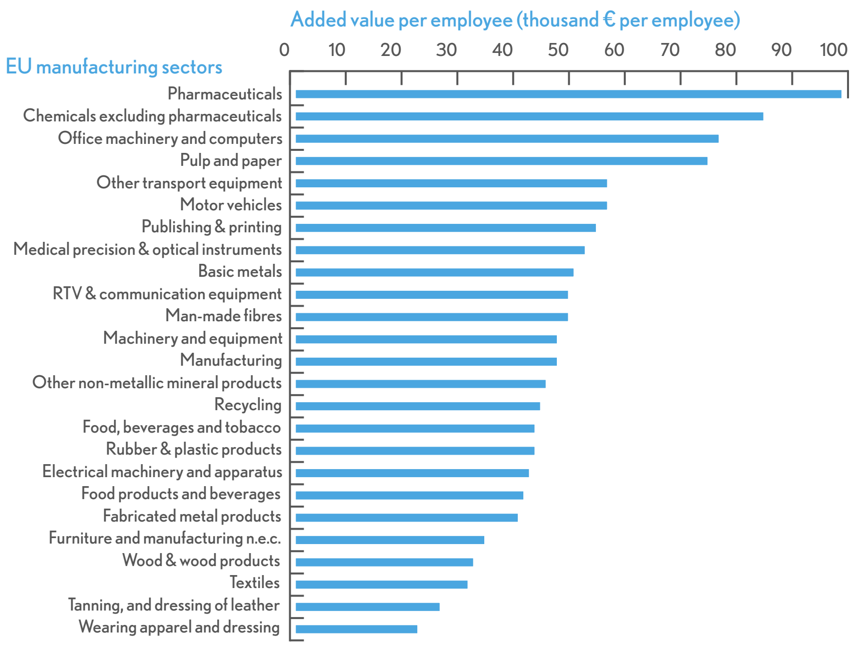


Figure 1.2: Added value per employee for EU manufacturing sectors.



New technologies

The industrial biotechnology market includes basic and fine chemicals, bioethanol, enzymes, active pharmaceutical ingredients, etc. Some recent reports (such as those by BCC Inc.[2] and Freedonia[3]) predict annual growth rates of nearly 5% for fermentation products (compared to 2-3% for overall chemical production) in the coming years, while others (such as the one by McKinsey & Company[4]) predict much higher growth rates and consequently estimate biotechnology to be applied in the production of up to 10% of all chemicals sold by the year 2010. Although numbers differ, all studies agree that industrial biotechnology will play an increasingly significant role in the chemical and other manufacturing industries in the future.

The greatest impact of industrial biotechnology, besides the fuel sector, is expected in the fine chemicals segment, where by 2010 up to 60% of products may use biotechnology in their production processes. A key driver here is the growth of biological pharmaceuticals for which no traditional chemical synthesis exists. The impact on the specialty chemicals segment will vary broadly. For instance, enzymes and fermentation are already used in the production of flavours and fragrances, while other markets may still be dominated by traditional chemistry through 2010 and beyond.

The first applications of industrial biotechnology in the large volume segments - polymers and bulk chemicals - have been commercialised. However, in these largely cost-driven segments, a number of technological advances and policy measures will determine the ultimate uptake of industrial biotechnology.

Industrial biotechnology will be one of the key contributors to the competitiveness of many of Europe's industries including chemicals, textiles and leather, animal feed, pulp and paper, energy, metals and minerals, as well as waste processing. The use of biotechnology in the chemical industry alone could generate significant additional added value through the realisation of lower costs for raw materials and processing, combined with smaller scale investments in the fermentation of plants, and through additional revenues from innovative, new, or performance enhanced products.

An important market for the chemical industry, and the EU as a whole, is the nanomaterials/nanotechnology sector. Conservative estimates predict an annual growth rate of between 10-15%, with an expected products market volume of €500 billion and components (nanoporous materials, formulations, nanocomposites, thin films and coatings, etc.) market volume of approximately €50 billion for 2010[5]. In particular, the nanotechnology machinery segment is expected to grow by 30% per annum[6] (see Figure 1.4).

Figure 1.3: Market potential of biotechnology.

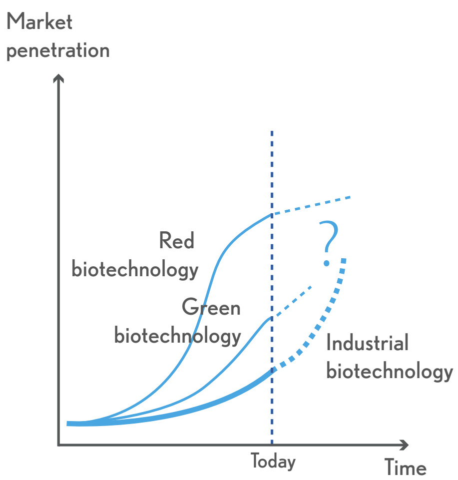
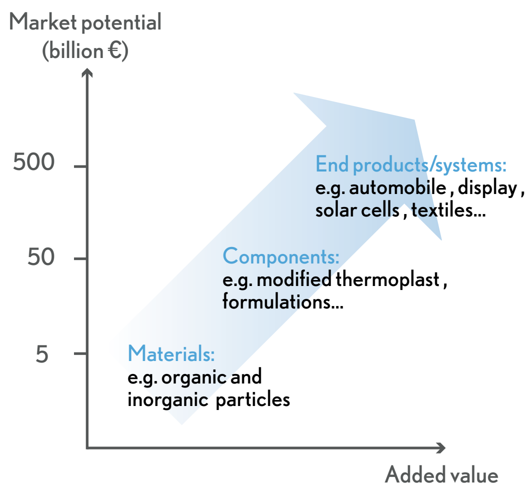


Figure 1.4: Market potential of nanotechnology.



To date the USA leads the nanomaterials/nanotechnology sector, but its research investment in the field is falling behind that of Asian nations and in particular China and Japan, who are spending almost double the funding on research. The European Union is lagging behind financially, yet curiously a significant number of papers and patents are published in the European Research Area. Various EU Member States have their own nanotechnology programmes, supplementary to EU programmes, but these are funded to a significantly lower extent than those of Asian nations (Taiwan, South Korea, etc.)[6].

An initiative, partially funded by the EU 6th Framework Programme, to outline the future activities in the nanotechnology field, called the NanoRoadMap Project has been created[7]. Its main objective is to produce a long-term (10 years) forecast aimed at highlighting the applications of nanotechnology in three important industrial fields: materials; health and medical services; and energy. The NanoRoadMap Project Report 2005 on Materials highlights the development needs for nanoporous materials, nanoparticles/nanocomposites, dendrimers, and thin films and coatings.

Research and innovation

The proportion of the EU(15) chemical industry sales (excluding pharmaceuticals) devoted to research and development in 2004 amounts to 1.8%, which is lower than both the USA (1.9%) and Japan (2.6%).

The leading academic research institutions and centres from the European Member States have been major contributors to the advancement in the knowledge of chemical science and biotechnology, and this has benefited the competitiveness of the European industries on the global markets. Traditionally these entities have been funded through regional or national resources, but the limited financial resources available are restricting Europe's ability to maintain this knowledge leadership, particularly when the competition presented by the US, East Asia and other emerging countries is considered.

Europe needs to be the world leader in chemical and bio technologies in order to promote industrial growth, to maintain a vibrant economy and to maintain social welfare. Innovations within chemistry, chemical engineering and biotechnology are flourishing in all sectors of the European economy, including environment, energy, agriculture, health, information and communication, infrastructure, construction and transportation. It is imperative for Europe to foster the cooperation, creativity and efficiency of the European researchers, by creating research centres of excellence in basic fields of research. This will not only provide impetus for new opportunities for European industries, but also secure the well-being of all European citizens.

3 Structure and Organisation

European Technology Platforms are a recent initiative by the EU Commission. The key objective of Technology Platforms is to define R&D priorities, timeframes and budgets in a number of strategically important issues with high societal relevance. Here, achieving Europe's future growth, competitiveness and sustainable development objectives is dependent upon major research and technological advances in the medium- to long-term. Technology Platforms are uniting stakeholders around a common vision and approach for the development of the technologies concerned, with specific focus on the definition of a Strategic Research Agenda and the mobilisation of the necessary critical mass of research and innovation effort.

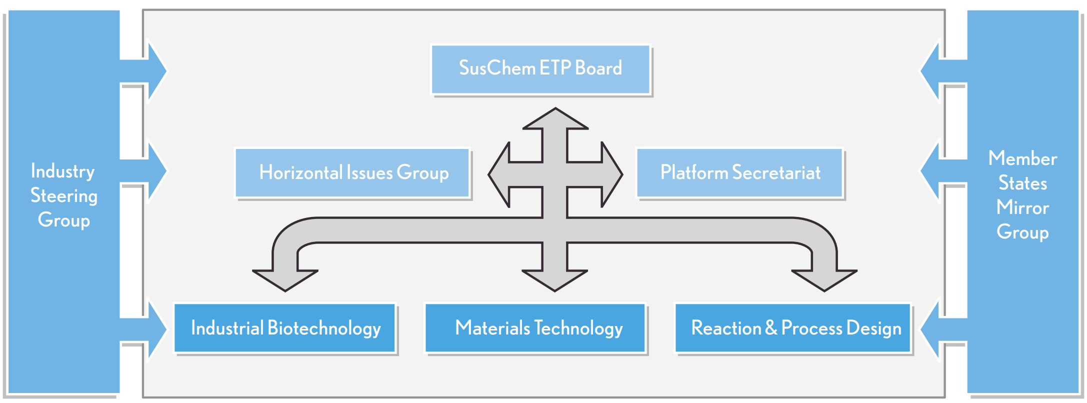
SusChem deliverables:

- Engagement with the wider stakeholder community in an open dialogue.
- An integrated, shared vision of a more sustainable future for the EU chemical industry.
- A Strategic Research Agenda for innovation in the prioritised technologies.
- An Implementation Action Plan for the Strategic Research Agenda that will include mobilisation of resources for collaborative R&D, sustain a strong European chemical science base, align relevant EU policies and initiatives and provide recommendations on improvements for EU innovation framework conditions.

The vision document was presented and endorsed by a major stakeholder event that was held in March 2005 in Barcelona. A wide variety of stakeholders were present in Barcelona, many of whom had previously worked on the vision document. Similarly, the present Strategic Research Agenda was endorsed by the 3rd SusChem stakeholder workshop that was held in November 2005, in London.

The organisation of SusChem is illustrated schematically in Figure 1.5. The platform comprises three technology sections - *Industrial Biotechnology, Materials Technology* and *Reaction & Process Design* - and a cross-cutting *Horizontal Issues Group*. A high-level board, consisting of nominees from the main stakeholder groups and representing the three technology sections and the *Horizontal Issues Group*, manages the Platform's overall activities. Essentially, the Board has a strategic role: it sets directions, policies and strategies. Two other groups also input into the Platform: the Member States Mirror Group and the Industry Steering Group. SusChem is supported by a secretariat.

Figure 1.5: The organisation of SusChem.



SusChem has strong links with many other Technology Platforms, illustrating the role of Sustainable Chemistry as an engine for major innovation in other industries. Likewise, SusChem covers almost all thematic priorities of the 7th European Framework Programme.

Synergies

1 Technology Platforms

Sustainable Chemistry has strong cross-sectorial importance beyond the chemical industry itself. Novel innovative materials are a prerequisite for new products and developments in many sectors, whereas advances in process design enable energy efficient, resource-saving and competitive production of such materials and give rise to process innovations in other sectors ranging from the electronics industry to energy production. Accordingly, a strong relationship between SusChem and a large number of other Technology Platforms exists, clearly illustrating the role of Sustainable Chemistry as an engine for major innovation in other industries.

SusChem can provide solutions for bottlenecks within these Technology Platforms on different levels, by:

- Providing enabling technologies.
- Enhancing the performance of products.
- Intensifying existing processes.
- Providing/exploiting/utilising new materials with targeted physical or chemical properties.
- Addressing societal needs.

Examples of the contribution of Sustainable Chemistry to other Technology Platforms and their respective sectors are given in Table 2.1, which also illustrates SusChem's most relevant relationships to these other Technology Platforms.

Table 2.1: SusChem's relationships to other relevant Technology Platforms.

Technology Platforms	SUSCHEM TECHNOLOGY THEMES		
	Materials Technology	Reaction & Process Design	Industrial Biotechnology
Hydrogen & Fuel Cells	Membranes, carrier/storage systems for e.g. hydrogen	Catalysis, CO_2 separation	Bio-based hydrogen sources
ENIAC - Nanoelectronics	Electronic materials		
ARTEMIS - Embedded Systems	Light weight, Semiconducting materials		
eMobility - Communication	Light weight, Semiconducting materials		
Photovoltaic	Materials with enhanced photon convertance	Synthesis and purification of materials	
Nanomedicine	Analysis of nanomedicines, improved drug coatings	Targeted encapsulation techniques	Enzymatic functionalisation of drug delivery materials
Innovative Medicine	Biocompatible materials, Materials for sensors	*In-silico* prediction of e.g. toxicology	
ACARE - Aeronautics	Light materials, energy saving		
ESTP - Space Technology	New materials for building vehicles, energy supply, recycling, next generation isolation materials		
WSSTP - Water Supply	Sensors, photoreactive coatings, nanostructured membranes for separation	Online monitoring, water purification, waste water treatment	Clean enzymatic processes
ERTRAC - Road Transport	Energy storage systems	Collaborative/inventory planning	Biofuels
TP Safety - Industrial Safety	Sensors, high-impact materials, Improved materials for personnel safety equipment	Safer processes, Risk assessment methods	
FTP - Forest Resources	Hybrid materials	Separation and purification technologies	Lignocellulose based biorefineries
MANUFUTURE - Manufacturing	Nanomaterials	Processing, lifecycles	
Plants for the Future			Biomass optimisation and crops for industrial use
Biofuels TP		Catalysts for syngas production from biomass, guard concepts	Biofuel production (esp. bioethanol)
Food for Life	New packaging materials, Increased bioavailability of nutritional supplements	Formulation engineering, Encapsulation	Use of organic waste as feedstock
ETP-FTC - TP for the Future of Textiles and Clothing	New (specialty) fibres		New enzymes & detergents, Innovative fibres, New processes, etc.

Relevance of SusChem for the other Technology Platforms	
	Low
	Medium
	High

2 Selected FP7 Thematic Priorities

To achieve the objective defined by the Lisbon European Council of March 2000 to make Europe "the most competitive and dynamic knowledge-based economy in the world" by 2010, European research must be strengthened. Advances in chemistry and industrial biotechnology, and new enabling processes and pathways leading to innovative products are a key element of a European research strategy. Accordingly, Sustainable Chemistry provides important enabling technologies for innovation in other industrial sectors which are particularly important for economic growth in Europe. At the same time Sustainable Chemistry contributes to the other pillars of the 'Lisbon strategy' by creating a highly qualified workforce and attractive employment opportunities, and by contributing to sustainable development and to protection of the environment.

European research and industry have a leading position in many areas of the innovative (bio)process technologies, in materials research, and in many of the markets and applications of advanced materials and processes. To sustain and further extend this leadership in global markets, a dedicated European research effort is essential. European industry is committed to technological progress in these areas and relies on a strong partnership with public research.

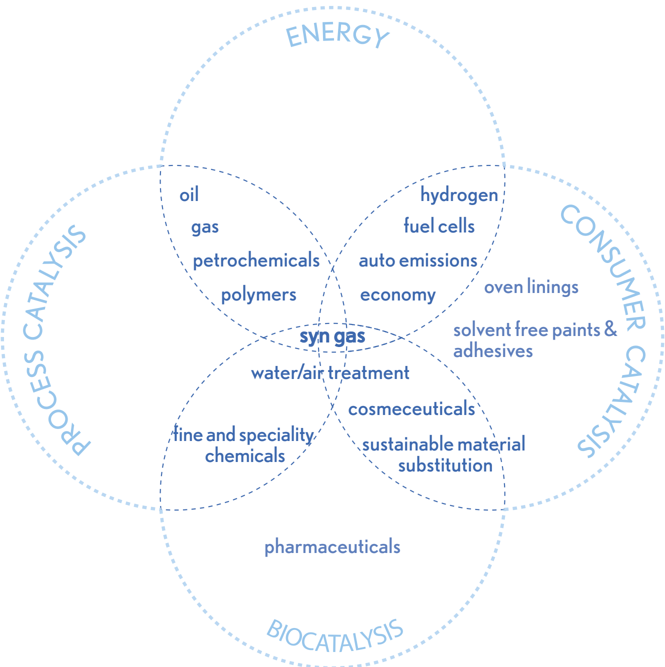
A future key to the success of this joint effort is collaborative research under the European Framework Programmes for Research and Technological Development. A significant number of the activities proposed by SusChem will find their place in the following thematic priorities: a) Nanosciences, Nanotechnologies, Materials and New Production Technologies (NNMP); b) Food, Agriculture and Biotechnology, and c) Environment. It is, however, also important to highlight possible contributions to other thematic priorities to demonstrate the enabling character of SusChem research. As an illustration the variety of interactions within the Seventh Framework Programme and beyond, the following examples describe how SusChem provides key contributions to some of these other FP7 thematic priorities. Numerous further examples covering almost all thematic priorities are depicted in the detailed research agendas of the three technology sections and the horizontal issues section in the Appendix to this document.

Thematic priority: Energy

Catalysis and process intensification efficiently harness energy resources

The World Energy Outlook 2002[8] provided by the International Energy Agency projects a continued rise in the demand for natural gas at least until 2030. While this increasing demand makes efficient production and processing of natural gas essential, large amounts of natural gas are usually lost as it is burned (flared) or released in the atmosphere (vented) during the production of oil and gas. A study undertaken by the world bank estimates, that approx. 108 billion m^3 of natural gas were flared in 2000, not only wasting substantial precious energy resources but also causing greenhouse gas emissions in the range of approximately 212 million metric tons CO_2 annually world-wide. In this context, catalysis is a key technology enabling gas to liquid conversion to synfuels and other chemical basic products, thereby providing efficient solutions to harness this "excess" gas. Flexible and economically competitive on-site processing of natural gas, perhaps even off-shore, is envisioned using mobile, compact production units utilising intensified equipment (see Figure 2.2).

Figure 2.2: Catalysis – one of chemistry's most important and powerful technologies.



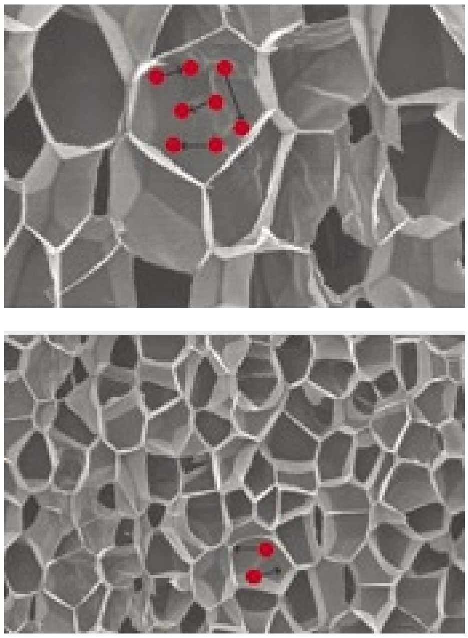


Figure 2.3: By shrinking the cell dimensions within the foam to within the scale of the mean free path of the gas molecules (< 100 nm) the gas based thermal conductivity becomes negligible[9].

Nanofoams save energy

In Europe a large proportion of energy consumption can be attributed to the generation of ambient climatic conditions and environments in houses, offices, buildings and vehicles. Private households in Western Europe consume approximately 25% of energy for these purposes. Whether this is in the form of cooling or heating, increases in efficiency and thus cost savings can be achieved by using appropriate materials to prevent energy losses. Foams have been used for a long time in various applications, from refrigerators to houses, as thermal insulators. The technology platforms ECTP (Construction) and Manufuture (Manufacturing) consider using the known foams in new ways to provide better insulation for houses and manufactured goods. Today, very efficient nanofoams already exist, but their production is not economically viable. SusChem can provide the know-how, through interdisciplinary work between chemists, physicists and materials scientists, and expertise, through its stakeholder network, necessary to not only improve current foams, but also to assist in the development of new variants, such as nanostructured materials.

Figure 2.4: An example of an efficient insulator: an inorganic aerogel protecting a flower from a flame[10].

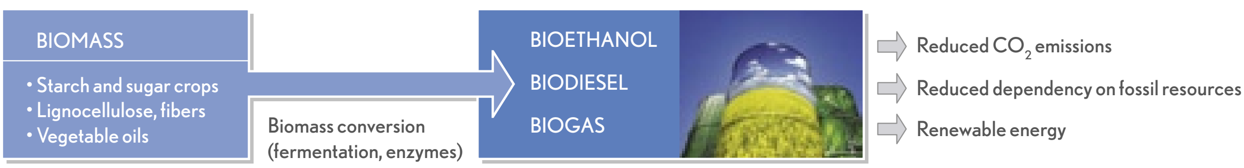
Nanostructured materials have the potential to revolutionise the insulation technology sector. These have a significant advantage over current foams in that they have a lower thermal conductivity even at reduced thickness. Over 60% of thermal conductivity can be attributed to gas diffusion. By shrinking the cell dimensions within the foam to less than 100 nm, the gas-based thermal conductivity becomes negligible. This leads to significant savings in energy, by making applications such as refrigerators or housing insulation more efficient, as these require less energy to maintain their internal temperatures. It is still necessary to scale-up to large production volumes of nanostructured materials and to incorporate these materials into industrial and commercial applications (see Figure 2.3, 2.4).

Renewable fuel production

Biofuels are the focus of growing interest for transportation. They can provide a reliable and renewable supply of energy as well as reduce greenhouse gas emissions into the atmosphere. Currently the most common biofuel is ethanol, the world production of which is lead by Brazil, followed by the USA. The European Union has recently set ambitious new targets[11]: by 2010, 5.75% of both petrol and diesel will comprise biofuels, rising to 20% in 2020.

Ethanol is currently produced from easily fermentable agricultural materials such as sugar cane (in Brazil), sugar beet or cereal grains (in the US and Europe). Industrial Biotechnology can improve existing fermentation or enzymatic processes, as well as provide new processes from diversified, cheaper sources of renewable raw materials, thus making the production of bioethanol more sustainable, efficient and cheaper. For example, yeast can be modified to produce ethanol directly from xylose (also known as wood sugar). Biodiesel based on vegetable oils could be produced using eco-efficient biological processes based on lipase enzymes to replace the current chemical processes. Biomass can also be fermented to produce alternatives to natural gas such as methane (an efficient and established technology) or hydrogen (still in the development stage).

Figure 2.5: Advantages arising from to the conversion of biomass to biofuels.



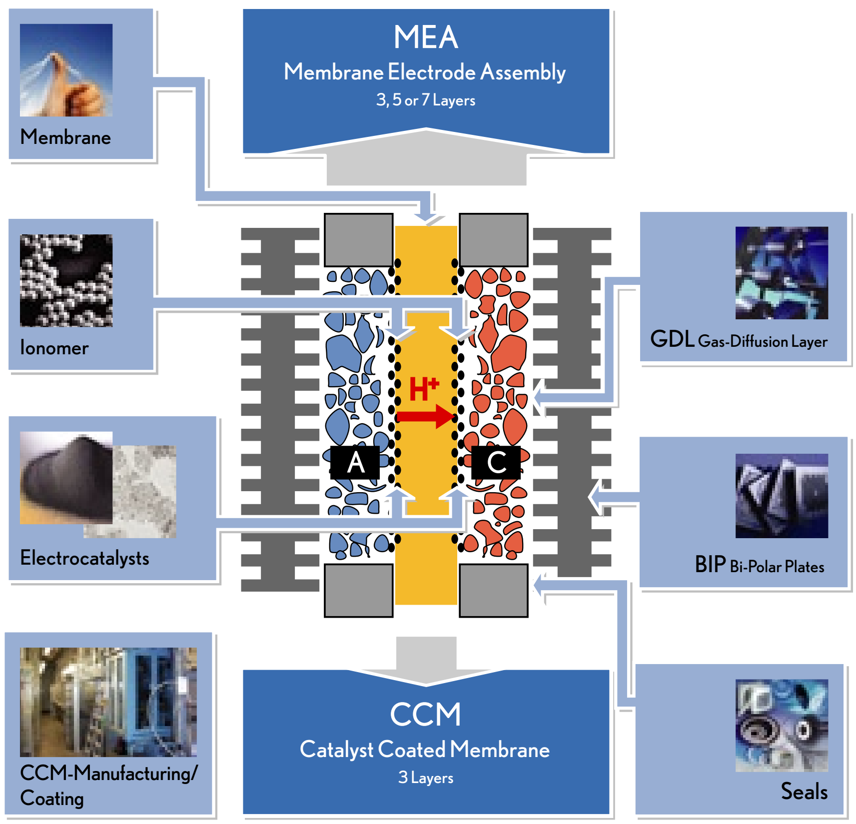
Thematic priority: Transport

Membranes enable efficient fuel cells

In the future fuel cells will play an important role in assuring the mobility of vehicles and electrical devices (laptops, mobile phones, etc.). One of the largest hurdles encountered in the development and production of fuel cells is their relatively low efficiencies. Naturally the catalyst used plays a significant role in determining the efficiency of the cell, but the inability of the membranes used to selectively transport protons between segments of the cell also impacts on the performance. In their vision documents the Technology Platforms hydrogen and fuel cells, photovoltaics, manufuture, eMobility (mobile and wireless communications) and EuMat (Advanced Engineering Materials and Technologies) either consider using fuel cells to achieve goals, or propose to pursue their further development in some form.

SusChem possesses the basic fundamental understanding of the processes involved and the interdisciplinary expertise of chemists, physicists, biotechnologists or material scientists, which can only be found in the SusChem stakeholder network. Membranes that are developed or produced through a biological process or through the application of nanotechnology, that can selectively and efficiently promote the transport of protons from one cell segment to another, have a better chance of being developed in the cross-cutting environment of the SusChem network. Naturally cooperation with the other ETPs can be beneficial (see Figure 2.6).

Figure 2.6: The components, materials and productions technologies necessary to construct a single cell of a fuel cell stack.

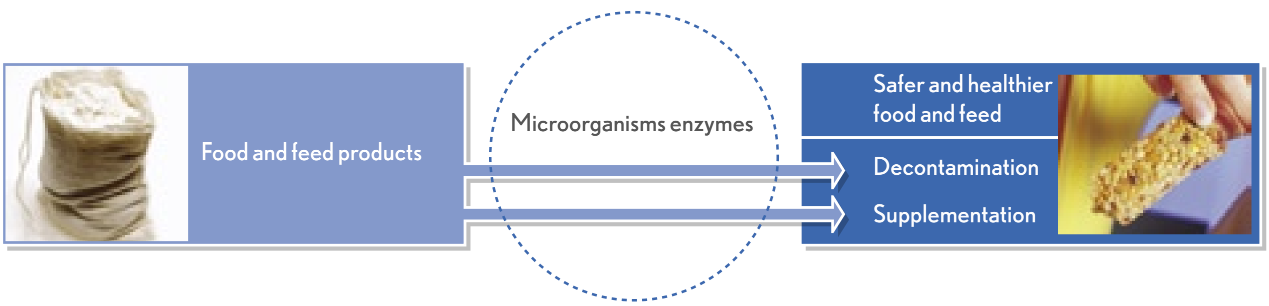


Thematic priority: Food, agriculture and biotechnology

Industrial biotechnology for safer and healthier food

Enzymes have long tradition of use in the processing of a variety of foods, including beer, cheese and vegetable oils. Now enzymes are also being developed to make foods safer. For instance, during the production of sweet baked or dried products the heating induces the formation of acrylamide, a potentially carcinogenic substance. Studies show that the application of an asparaginase during processing decreases the acrylamide content by at least 70%, making food safer. Modern industrial biotechnology processes make it possible to produce asparaginase on a larger scale and at reduced costs. Industrial biotechnology can also produce important compounds for health such as vitamin B2, which is essential for the growth and production of red blood cells, antibodies and cells, and aids in releasing the energy from food. Traditionally, vitamin B2 is synthesised by a multi-step chemical process from glucose. This can now be replaced by a single step biological process, making the process cleaner and cheaper for food and feed supplementation. Research is also concentrating on having products such as B-vitamins directly included in the food production process, for example, in dairy products such as cheese via the modification of lactic acid bacteria (see Figure 2.7).

Figure 2.7: Industrial biotechnology allows for safer and healthier food and feed.



Major contributions from the chemical industry stemming from innovation in products and processes will be essential to further promote sustainable development and bolster the future of the chemical industry in Europe.

People, Planet, Profit

As the world changes it presents new opportunities and challenges for both the chemical industry and for European society. Globalisation, progress in telecommunication and data transfer, finite resources (soil, energy, water and arable land) and worldwide population growth, coupled with aging societies, are the most significant trends determining the future of the planet.

Safeguarding food and water supplies, development of alternative and renewable energy resources, and improvement of healthcare systems, are indispensable prerequisites to achieve prosperous and peaceful global development for an increasing world population. These objectives are best pursued through a balanced effort that takes into account economics, environmental protection and quality of life. Major contributions from the chemical industry supported by new research are necessary to meet these challenges.

Some specific examples will better demonstrate the impact of global trends and challenges on the demands for technological development in the areas of chemical and process engineering, new materials and industrial applications of biotechnology.

1 Societal Drivers

Energy

The total world consumption of energy in 2003 was 14 Terawatts 70% of which originated from oil or coal; it is predicted that the energy need for 2050 will be between 30 to 60 Terawatts. This increase presents a serious challenge for the current technologies.

There are some important global trends which will drive changes in the technology base over the coming few decades, and nowhere are these more critical than in Europe. The key challenges are:

- Continuing increases in energy use, particularly in the transport sector.
- Limits to the quantities of fossil resources extractable at an economically viable cost.
- Continued world population growth over the next half century.
- Increasing pressures to make the changes to ensure growth is sustainable.

In considering the contribution of materials technology, the energy problem can be divided into the following topics:

- Energy generation: this includes current technologies from fossil fuels, alternative technologies for renewable resources, such as solar, hydro, wind, geothermal, biomass for biorefinery and nuclear. In the case of materials technology the focus will be on fuel cell technology and photovoltaics.
- Energy transmission and distribution: this includes heat networks, electric wire and electric grids.
- Energy storage: batteries, superconductors, hydrogen storage, etc.
- Energy management: insulation in buildings, more efficient lighting, lighter materials for transport, minimisation of energy losses, etc.

Without new discoveries in material science the required breakthroughs in any of the above areas will not be possible.

In energy production and transportation, new materials with useful conducting and superconducting properties will have a significant impact on society in practical systems for the transmission of large electrical currents over long distances without energy losses. New ceramic materials will play an important role in this area.

In the area of energy management and conservation, new materials with lightweight construction will greatly enhance the efficiency and environmental sustainability of surface and air transport.

Reaction and process design can contribute through new cheaper synthetic processes with a reduced number of steps, using innovative energy sources (like microwaves, plasma), new solvents and reagents (like water and ionic liquids) and new reactor concepts; some of these are already available for industrial implementation in many fields. These provide energy-efficient and waste-free routes to a wide range of target molecules and take advantage of novel feedstocks hitherto unused in chemistry.

With oil prices steadily climbing, other alternative feedstocks, such as gas and coal could become very attractive. Europe should prepare to tap into these raw materials for chemical production. Short-term targets are direct oxyfunctionalisation processes for methane, longer-term research should focus on energy-efficient and clean technologies for making use of gas and coal in chemical production.

As a result of the limitation of fossil fuel extraction and the continuous increase in energy demand, there is a growing demand for improved security of supply and increased energy efficiency. Industrial biotechnology has an important role to play in developing an alternative to conventional fossil feedstocks: Biomass, i.e. agricultural raw materials such as cereals which, in contrast to oil, have become cheaper as farming yields have increased. Weight-for-weight, agricultural raw materials are generally less than half the cost of fossil fuels. Some, such as straw (which accounts for about half the biomass in a field of cereals) have a market value of only about 10% of that of oil. All are grown in large quantities in Europe. Biomass can also be fermented to produce methane (an efficient and established technology) or hydrogen (still in the development stage). Either of these could be a partial replacement for natural gas.

Information and communications technology

In modern society communication, information and entertainment is one of the largest market sectors. The electronics industry continually seeks new materials for superconductors, polymeric conductors and semiconductors, dielectrics, capacitors, photo resists, laser materials, luminescent materials for displays as well as new adhesives, solders and packaging materials.

The development of new materials in the field of optical data transfer will be extremely important: non-linear optics materials, responsive optical materials for molecular switches, refractive materials and fibre optics materials for optical cables are all important areas for research. Another example is in the area of conforming materials for electronic paper as an alternative to conventional books, newspapers and magazines. The challenge lies not only in the development of new materials with the desired properties but also in their effective incorporation into functional systems.

Healthcare

As a result of the increase in life expectancy and the aging population, a new paradigm is required to provide optimal and personalised medical care. Resources must be invested in prevention measures in order to reduce increasing medical costs.

There is a need for new materials for implants, drug delivery, and novel therapeutics, but also for health protection and care, diagnostics, and sensors for prevention and timely detection of serious diseases.

Sensor technology provides a connection between biological function and an electrical signal. Advanced sensors and new micro-analytical devices will have a substantial impact on health, environment, and individual protection strategies in the coming years.

The ability to reliably link biologically active molecules to a surface will provide huge opportunities for improved medical devices and drug delivery strategies. Another aspiration is the design of materials that mimic the behaviour of physiological systems such as muscle.

Software tools for the assessment of physiological properties of substances that combine validated mechanistic prediction models with powerful visualisation and selection features already play a major role in drug discovery. With the improvements in technology associated with the reaction and process design area, they will be able to handle ever larger numbers of compounds, with greater accuracy and for more complex systems. The high quality estimates of properties, which have previously only been available from *in-vivo* experiments, are based on elementary physicochemical properties of the compounds. Since these data will increasingly be determined *in-vitro* using high throughput methods, or be predicted *in-silico*, there will be very early rationally based assessment of physiological behaviour of drug candidates.

Industrial biotechnology can contribute to make the European pharmaceutical industry more competitive by developing more efficient pathways for drug production or by using bioprocesses to produce drugs which are difficult or impossible to synthesise chemically.

So-called Advanced Pharmaceutical Intermediates (APIs) are key building blocks for the synthesis of sophisticated drug molecules. One of the key reasons to favour a biological route for their production is that many of the products come in either "left-handed" or "right-handed" forms (so-called chiral molecules), only one of which is physiologically active. Enzymes will selectively produce only the active form, whereas chemical synthesis typically produces a mixture which is difficult to purify. As APIs are becoming more complex with multiple chiral centres, bioprocesses are increasingly gaining in importance.

Antibiotics (a global market worth €20 billion) are made almost exclusively by fermentation using specially-selected microorganisms. Antibiotic molecules are so complex that conventional chemical synthesis has never been a realistic alternative. In some cases, semi-synthetic antibiotic molecules are made by chemical modification of the molecules produced by fermentation, to give improved performance. Even these modifications are now increasingly being performed using biotechnology, giving both economic and environmental benefits.

Biological processes are also key to the production of other major drugs. For example, the Angiotensin-converting enzyme (ACE) inhibitor Captopril™, used to treat high blood pressure, is produced from two building blocks, each produced by fermentation (in one case by a yeast, in the other by a bacterium). The final step of linking the two intermediates is then carried out using conventional chemistry.

Complex biomolecules such as antibodies, peptides and proteins are increasingly being used in medicine, and many of these are produced by culturing cells derived from microorganisms, plants, animals and humans.

New biopolymers can also be used to control the release of drugs or nutrients.

Finally, nutraceuticals and food additives can be produced directly by microorganisms. The efficiency of the production can be enhanced, and as well as new production pathways developed, by metabolic engineering.

Quality of life

The quality of life of European citizens is expected to be enhanced dramatically by the use of new materials for devices enabling greater mobility, e.g. mobile phones, portable computers, etc., more efficient and sustainable transportation, cosmetic preparations for better appearance and protection from external environment, and improved nutrition by increasing the stability and bioavailability of vitamins and food additives through innovative formulation techniques.

Smart internal and external coatings can be developed with self-cleaning properties and which are switchable depending upon changes in the environment. Surfaces with anti-fouling properties able to recognise and destroy pollutants and corrosion agents can be produced. New materials are required to enable the production of longer lasting batteries; smaller and more stable sensors; functional clothing that is self-cleaning, adapting and protecting; and prosthetics and implants.

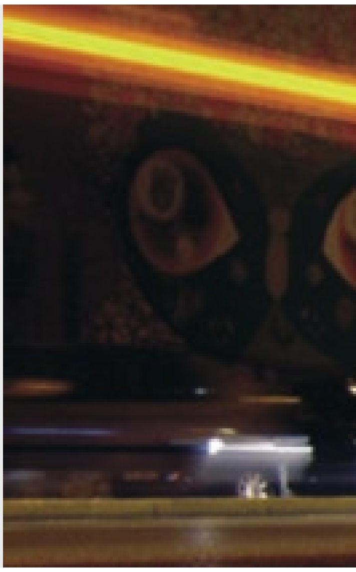
Next generation catalysts from within the reaction and process design area should contribute to achieving zero emissions. New catalysts will also enable the development of new biomimicking catalytic transformations, new clean energy sources and chemical storage methods, utilisation of new and/or renewable raw materials and reuse of waste, solving global issues (greenhouse gas emissions, water and air quality) and realising smart catalytic devices for health protection and the improvement of the quality of life, such as "self-cleaning" ovens or tiles that are self-cleaning or prevent algae growths.

The major impact of industrial biotechnology will be to help industry create economic value while reducing the impact of industry on the environment. Industrial biotechnology can contribute to greater efficiency and reduced waste by developing tailor-made bioprocesses for industrial use. Typically, one of the major long-term benefits will be its contribution to the reduction in carbon dioxide emissions.

Moreover, as environmental awareness grows, the demand for products from clean, green manufacturing processes will grow:

- Biodegradable plastics made from starch.
- Biodegradable detergents with enzymes.
- Mild processes for textile treatments and new fibres for textile industry.
- Cheaper food, feed and nutritional additives.
- Management / "recycling" of industrial wastes into high value products.
- Enzymes for the removal of allergenic or carcinogenic compounds in food.

For these reasons the products of industrial biotechnology will be even more attractive: they will be seen by many as premium products rather than like-for-like alternatives.



Citizens' protection

Society has been increasingly challenged by accidents, terrorist attacks, sudden climate changes and catastrophes causing extensive personal and material damage. There is a need to develop new intelligent technologies in order to protect the civilian population from these extreme situations as well as to provide new ways of predicting and avoiding them. Sensors for explosives, toxic agents and biohazards at low concentration; materials for protection of people, buildings, (e.g. hospitals and airports), and vehicles; and functional textiles that recognise and destroy toxic agents or administer the right counteragents; can all be developed.

In addition, new sensor systems could help to detect chemical or biological threats and play an important role as components of security systems. Biometric identification and non-stop security checks, and smart cards for the storage of biometric data will help to protect people and transport systems without time consuming security checks.

The resultant products and technologies will be beneficial for the manufacturing sector in ensuring safety at the workplace, by detecting hazards present, for example, nanoparticles. The Technology Platform on Industrial Safety addresses some of the safety concerns raised here in more detail.

Transportation

Mobility of citizens and transportation of goods in the growing European Union requires the development of new and more efficient transportation systems. For the preservation of natural resources, quality of life and the environment, new material concepts and fossil fuel free vehicles have to be developed. Recyclable and improved, light-weight functional materials and sustainable materials management and alternative energy sources will help to reduce greenhouse gases and improve the quality of life for citizens.

New driver assistance systems, protective systems and traffic management sensors have to be developed to ensure that the high safety standards can follow the increasing volume of traffic in the European Union.

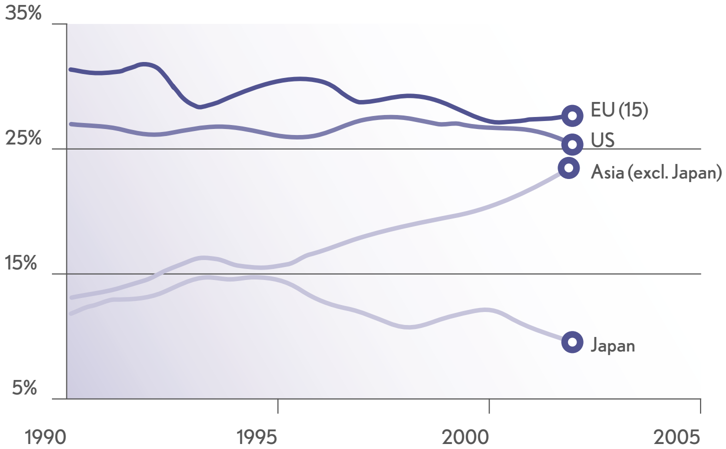
In the realm of industrial biotechnology biofuels are the focus of growing interest for transportation. In the case of road transport, bioethanol and biodiesel are beginning to have a significant impact on the mix of fuels in some countries. Mixed with conventional fuels, they can not only be used in standard engines without modification, but also improve combustion and reduce CO_2 emissions.

2 Challenges and Opportunities

A recent study conducted by Cefic[12] concluded that the competitiveness of the chemical sector is declining. The European chemical industry has reached a phase of maturity; many products have become commodities subject to strong competition particularly from Asia. Markets in Europe are stagnant, whilst strong growth occurs in China. The current leading position of the EU in chemical manufacturing is already slowly eroding because of the dynamic development in Asia; the EU(15)'s share of global output has declined from 32% a decade ago to 28% today.

Further investment in chemicals is not particularly favourable in Europe, because of low returns on investment due to a combination of relatively high production costs, high costs associated with meeting the requirements of regulations, the changing regional balance in manufacturing in customer sectors, and the absence of good feedstocks. The EU needs innovative leadership to reduce or even reverse this trend and to beat international competition. Enhanced knowledge and skills are a necessity for this process. (see Figure 3.1)

Figure 3.1: Global share of chemicals market.



The Cefic competitiveness study developed different scenarios with a 2015 time horizon. A defining part of the most optimistic scenario is a chemical industry focused on innovation, thus innovation is the key driver for the future competitiveness of the sector and its associated supplier and customer industries.

R&D, next to customer relationships, is recognised by most chemical companies and downstream users of chemicals as a key driver for innovation. However, the current focus on financial performance, frequent restructuring programmes and increasing regulatory costs are limiting R&D spending in industry, which structurally underperforms in comparison to the USA and Japan. As chemistry is the basis for many innovations in other sectors[13], this has wider repercussions for the European manufacturing sector and for the provision of knowledge and skills. Furthermore, public European efforts are fragmented and public private partnerships are not yet fully developed. This places Europe at a competitive disadvantage relative to its main competitors: competitors that are generally recognised to provide more supportive environments for innovation.

Due to the decrease in market share and with increasing labour productivity, employment in the EU(15) chemical industry has decreased by 16% over the last ten years to 1.7 million, and by 40% in Central and Eastern Europe to one million.

Partly as a result of this Europe is witnessing a sharp decline in the number of students graduating in chemistry and chemical engineering. If the sector is to remain innovative and continue to grow, then this must be reversed. This requires education systems that present chemical sciences and technologies as an essential and relevant part of modern society as well as an industry clearly communicating and committing to its longer term needs and requirements.

The image of chemistry is an important factor in attracting potential students; explicit attention to sustainable chemistry and engineering in secondary and tertiary education could contribute positively to engaging the minds of the next generation.

To provide guidance in setting priorities for the SusChem technology areas, a strategic assessment of the factors influencing the chemical industry with a special focus on innovation was performed (see Table 3.1).

The SusChem strategic research agenda was developed with this analysis in mind, focusing on current strengths and especially future opportunities for the industry. Downstream users have been involved to ensure that SusChem addresses their future needs. Innovation in products and processes will be essential for the future of the industry in Europe.

Table 3.1: Strengths, weaknesses, opportunities and threats relating to SusChem and the chemical industry.

Strengths	Weaknesses
• EU has a good chemical manufacturing infrastructure • EU has the most efficient production capability in terms of resource use and CO_2 emissions • EU has a supply of highly skilled workers • World-leading in chemicals (pharmaceuticals and fine chemicals), enzymes and (bio)specialities • Access to a wide diversity of renewable resources in the EU	• Shortage of entrepreneurs • Slow translation of R&D into commercial products • Shortage of some skill sets to exploit new opportunities • Shortage of specialist technology institutes • Insufficient funding for R&D • Lack of awareness among industry of biotechnology applications • Insufficient coordination of national and EU research programmes
Opportunities	**Threats**
• The EU is better placed than its competitors to develop innovative, world leading products based on its highly successful chemicals sector • The EU is well-placed: - to become the market leader in sustainable chemistry - to build on its world-leading position in industrial biotechnology to gain competitive market advantage - to exploit increasingly stringent global environmental targets	• Competition from US and Asia • Lack of societal acceptance of new products and processes • Risk of chemical companies leaving the EU • Inappropriate regulation and excessive bureaucracy (shifting production to regions with lower standards) • Unfavourable fiscal and monetary conditions

3 Development Priorities

The list of (potential) development priorities is long: in order to provide a coherent picture of these, roadmaps for products and technology developments for energy, information and communication technology, healthcare, quality of life, citizen protection and transportation have been created. These roadmaps provide guidelines and set the priorities (medium, high and essential) over the given time frames (short-, medium-, long-term) for research topics. For each product the current development status, the current or potential market volume and potential market success have been listed. Associated with each product roadmap is a technology roadmap, indicating which technology developments are required to achieve and realise the products listed in the roadmaps. As an example, the product and technology roadmap for energy is described below. The other product and technology roadmaps for information and communication technology, healthcare, quality of life, citizen protection and transportation are discussed in detail in the Appendix A.

Since new results and insights influencing these roadmaps are gained every day, SusChem aims at updating its roadmaps on a regular basis.

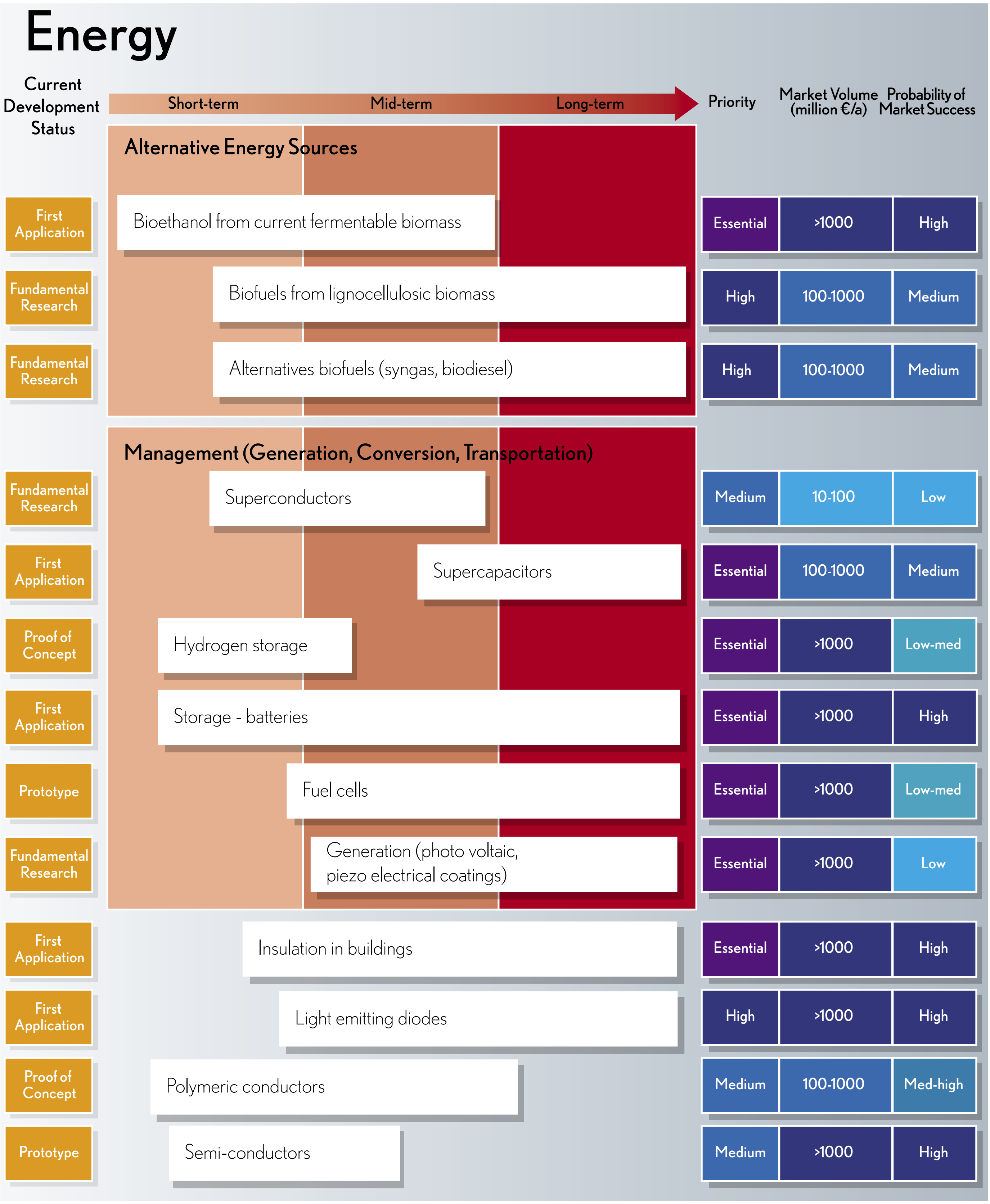
Products and technologies for energy management

Energy will become an ever more expensive commodity, and therefore there is a great need to manage this resource effectively. New products made from advanced materials can have a large impact by providing better storage, consumption or transportation of energy.

Product roadmap: Alternative energy sources

Alternative sources of energy such as solar cells, fuel cells and renewable primary products are currently being investigated. The degree of success and implementation of the energy creation technologies mentioned above depends on developments in material science, which will overcome the current limitations of performance, stability and costs. For example, if solar cells are to provide an alternative to fossil fuels, significant research needs to be done to develop new routes of crystalline silicon production, in the development of amorphous silicon hybrid materials, which could result in enhanced efficiencies, in concerted efforts for cheaper and more stable dyes, and in improving the efficiency of the dye sensitised cells. The development of the fuel cell, from prototype via small-scale production, to a mass product, can only happen if significant improvements are made to individual key components, and the corresponding contributions from the world of chemistry are absolutely vital. Material science needs to provide new proton exchange membranes that work at higher temperatures and new ecological catalysts for the reforming reaction.

Figure 3.2: Product roadmap for energy.



Product roadmap: Energy management
Various technologies could play a vital role in managing energy in the future, from making processes more efficient (catalysts, biomass conversion, plant management), to realising new developments (membranes for fuel cells, biorefineries).

New materials with conducting and superconducting properties will have a significant impact in practical systems for the transmission of large electrical currents over long distances without energy losses. New types of longer-lasting rechargeable batteries able to store more energy per volume and per weight are required for mobility (to power cell phones, laptops etc.) and for increasing the efficiency of the hybrid engines used for transport.

Substituting steel with lighter polymeric materials in automobile construction, together with increased efficiency in the use of petrol and diesel through the addition of additives, will reduce the consumption of fuel in cars (see Figure 3.2).

New insulation materials in the household already contribute to the construction of three-litre houses, i.e. houses that consume less than three litres of fossil fuel per square meter per year (30 kWh/m^2). Further, important products and technologies such as solar cells and active phase-changing materials (useful for controlling the climate within the house) play a vital role in saving energy. New nanoporous insulating materials can provide enhanced insulation. Efficient lighting in the form of light emitting diodes could replace the light bulbs based on tungsten wire and fluorescent tubes.

Thermoelectric devices are solid-state systems that can convert heat into electricity. In the process they provide cooling and precise temperature control. Tiny dots of thermoelectrical material could convert the waste heat produced by automobiles or microprocessor chips to produce electrical energy and as a result cool them.

To achieve these goals a number of technologies need to be either improved or developed. A couple of examples are illustrated in the technology development roadmap (see Figure 3.3).

Technology development roadmap: Alternative energy sources
One of the most challenging tasks will be to adapt and change the chemical industries' dependence on fossil fuels. There are three aspects that could be pursued in conjunction with one another, the replacement of oil (fossil fuel) through gas, coal and bio-based feedstocks. This would require a lot of technological adjustments to the production processes, depending on the source being utilised. Related to this is the utilisation of bioprocesses to generate biofuels from appropriate biomasses. Technologies, which enable the production of H_2 in a clean form, such as new catalysts, also present a viable option.

Technology development roadmap: Energy management
Various technologies could play a vital role in managing energy in the future, from making processes more efficient (catalysts, biomass conversion, plant management), to realising new developments (membranes for fuel cells, biorefineries). Associated with this is the appropriate development of production process scale-up, control technologies and analytical techniques for the production of materials and for plant operations and control.

Figure 3.3: Technology development roadmap for energy.

Energy

Current Development Status	Technology (Short-term / Mid-term / Long-term)	Priority	Market Volume (million €/a)	Probability of Market Success
	Alternative Sources			
Fundamental Research	Replacement of oil by gas, coal and biobased feedstock for chemical production	Essential	>1000	Low-med
Fundamental Research	Efficient catalytic solutions for clean energy production (e.g. based on H_2)	Essential	100-1000	Medium
Fundamental Research	New bioprocesses for biomass conversion to biofuels	Essential	100-1000	Low-med
	Management			
Fundamental Research	Biotechnological production networks in biorefineries	Essential	100-1000	Medium
Fundamental Research	Scale-up processes for the production of advanced materials	High	>1000	Medium
Prototype	Catalysts for alkane functionalisation, gas-to-liquids and biomass conversion	Essential	>1000	Low-med
Fundamental Research	Membrane technology	Essential	100-1000	High
Prototype	Energy efficieny production processes and plant management	Medium	>1000	Medium
First Application	Analytical techniques for the quality control of advanced materials	High	100-1000	Medium
Fundamental Research	Process development and control technology	High	100-1000	High

4 Socio-economic and Environmental Impact

Results from the research proposed in SusChem's SRA will impact almost all areas of our society, and further promote sustainable development in Europe. The research will help to solve current and future problems and issues arising from an increasing world population and that population's demand for ever more and better products and services. A few examples of the possible impact have already been described in this chapter when addressing the question of societal drivers (1. Societal Drivers) for this research agenda.

In the following sections three truly visionary project ideas will be described that give an impression of what will be possible in the future using the results of SusChem's proposed research. These project ideas, though not possible with today's knowledge base, will deliver tremendous benefits to society, the environment and the economy. Their description has been simplified to make it easier to follow and show their impact on our daily life in the future.

The energy-generating home: Smart materials and energy management

Energy and energy sources are a major focus of social life today. While most houses still rely on traditional, non-renewable means for their energy requirements, technological advances and resource management techniques have made it possible to cut energy consumption by up to 90% today. In the near future, innovations will make it possible for a home to generate enough energy to meet and even exceed its daily requirements and therefore eventually contribute to increasing a power grid's overall resources.

Ground-breaking technologies and smart materials make this vision possible by reducing heat loss, improving energy efficiency and absorbing and transforming energy into electricity.

Basic heat and electricity requirements will be considerably lowered with future technology. Radiant barriers in ceilings and walls will reduce heat loss by over 50% by reflecting or absorbing infrared radiation. Electrochromic "smart" windows will deflect or let in outdoor light by varying their darkness, therefore reducing energy use for lighting. In addition, white organic light emitting diodes (OLEDs) will replace current fluorescent light tubes, hence reducing energy consumption while emitting more light.

Such energy-efficient materials can easily be supplied with enough power by incorporating photovoltaic (PV) solar-energy panels into various surfaces of the house, such as the roof, but also walls and windows, as new PV materials will be cheaper and more flexible in their use. In addition, a small roof wind turbine could supplement the solar energy, while new materials will allow houses to transform various forms of energy, such as kinetic energy from movement, into electricity. Houses will be equipped with a control centre, allowing home owners to monitor and manage their energy use.

These advances in technology will allow houses to turn into self-standing, renewable energy power plants. A Micro-CHP (Combined Heat and Power) System in the house would also allow independence from commercial power plants by generating energy from any source, including potentially a hydrogen fuel cell. Any unused energy generated from these combined sources (solar, wind, kinetic, hydrogen...) could be returned to the electric "grid", therefore contributing to overall energy capacity and increasing sustainability (see Figure 3.4).

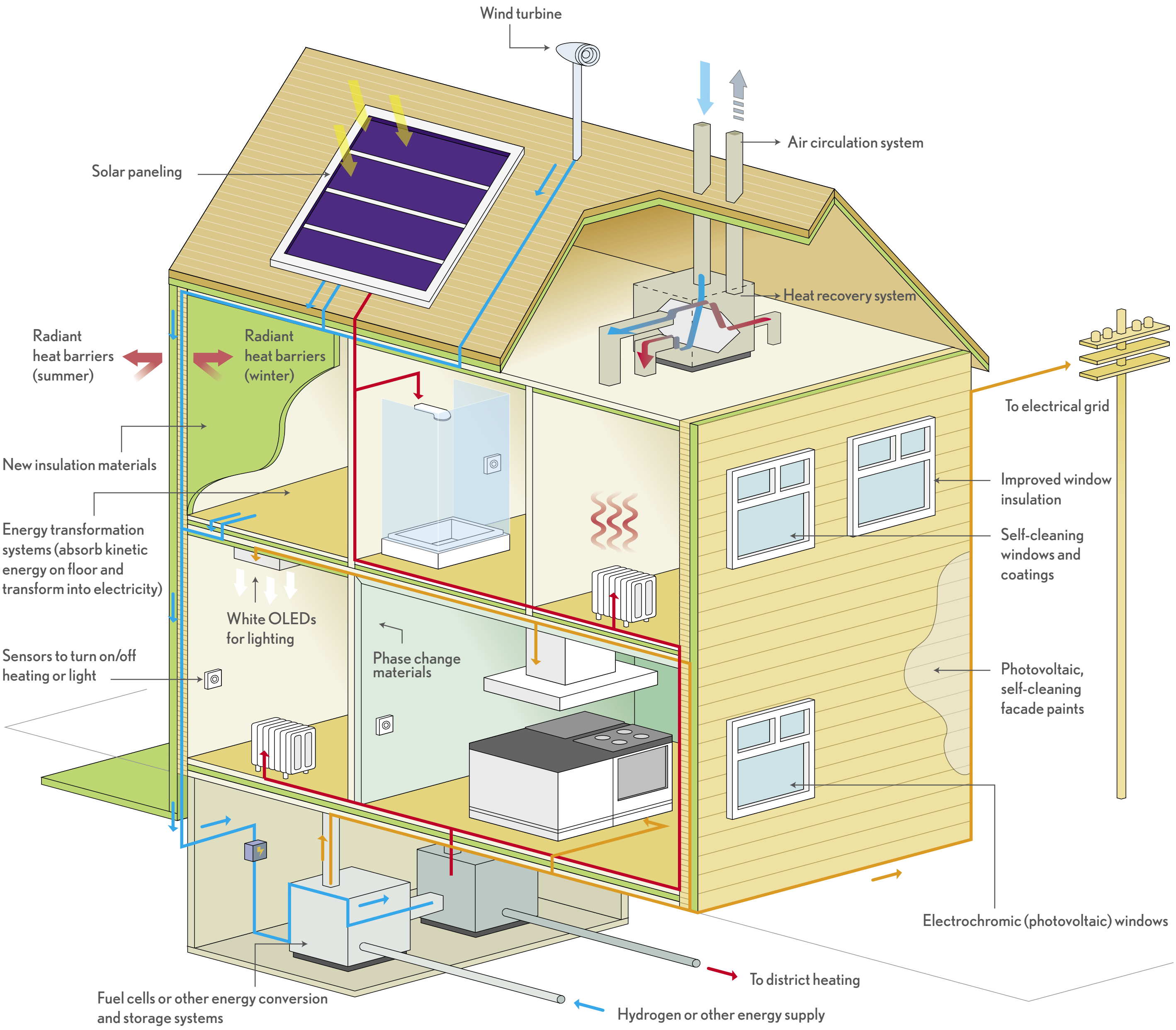


Figure 3.4: The energy-generating home.

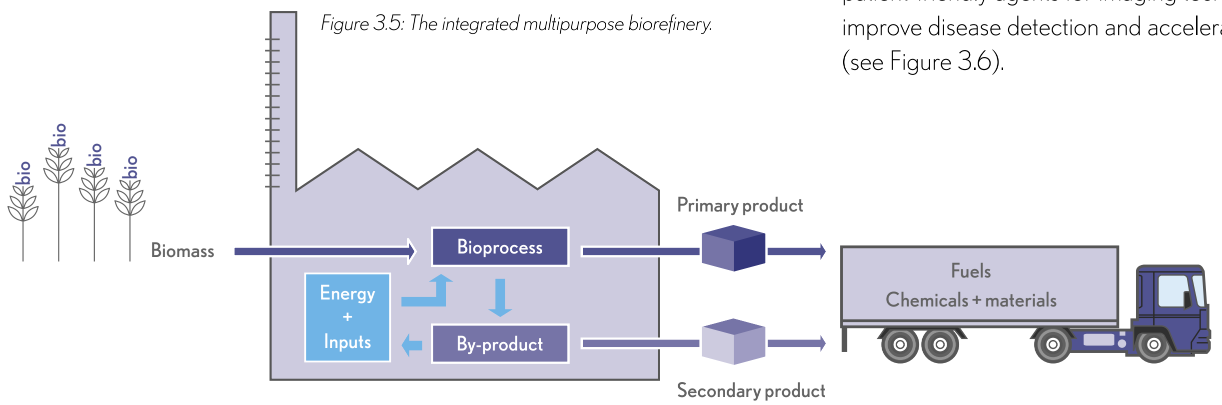
Biorefineries: Chemicals and energy from biological material and processes

Sustainability in chemistry can greatly benefit from the use of biological raw materials and processes. Biorefineries can provide ecologically smart solutions to transform crop or biomass into intermediates and products for use in society.

Improving on current biomass conversion techniques, these new refineries will use standard feedstock, but also eventually raw biomass and organic waste, for production. Integrated and diversified biorefineries will cover the entire value chain, not only by using different types of raw materials, but by developing the most adequate and efficient bioprocesses to produce a wide range of products, including newly designed high value products and materials. They will exploit all elements of biomass, reusing all secondary products and by-products of the reaction by either further processing them or by integrating them in the bioprocess as input or energy. These refineries would therefore produce little if any waste or emissions, significantly minimising pollution from industrial processes.

Such developments in industrial biotechnology will only be possible if renewable raw materials are produced in sufficient quantity and quality, at competitive prices. Research should concentrate on developing efficient ways of converting plant cells into fermentation sugar. Furthermore, new bioprocesses will be needed to transform the products of fermentation into high-value bioproducts (see Figure 3.5).

Figure 3.5: The integrated multipurpose biorefinery.



Personalised healthcare: Integrating monitoring, prevention and treatment

An ageing society means that our requirements in long-term healthcare will increase greatly over time. Today, health monitoring and treatment is often intrusive, costly and impersonal due to the limitations of medical technologies and facilities. Revolutionary advances in technology will not only improve the efficiency of medical interventions but personalise healthcare to make it a more integrated part of daily life.

New developments in medical technology and materials will allow for remote monitoring of at-risk patients coupled with the ability to activate quickly treatment when required. For example, intelligent clothing fitted with nanosensors will record parameters such as blood pressure, pulse and body temperature, which can then be communicated instantly to a doctor. Active delivery systems, releasing drugs, vitamins or nutrients into the body when certain conditions occur (such as increased heart activity or high temperature), would act as the first line of precautionary medical attention in response to an emergency or stress situations (stroke, migraine...) The "lab on a chip", an integrated microprocessor capable of data analysis, would enable early detection and diagnosis of illnesses or diseases, and combined with the smart delivery system could provide a fully personalised healthcare system supervised remotely by a physician.

Quicker, more reliable diagnostics using new types of biosensors and biochips will allow medicine and medical tests to be less intrusive in patients' lives. Similarly, new, patient-friendly agents for imaging technologies will improve disease detection and accelerate intervention (see Figure 3.6).

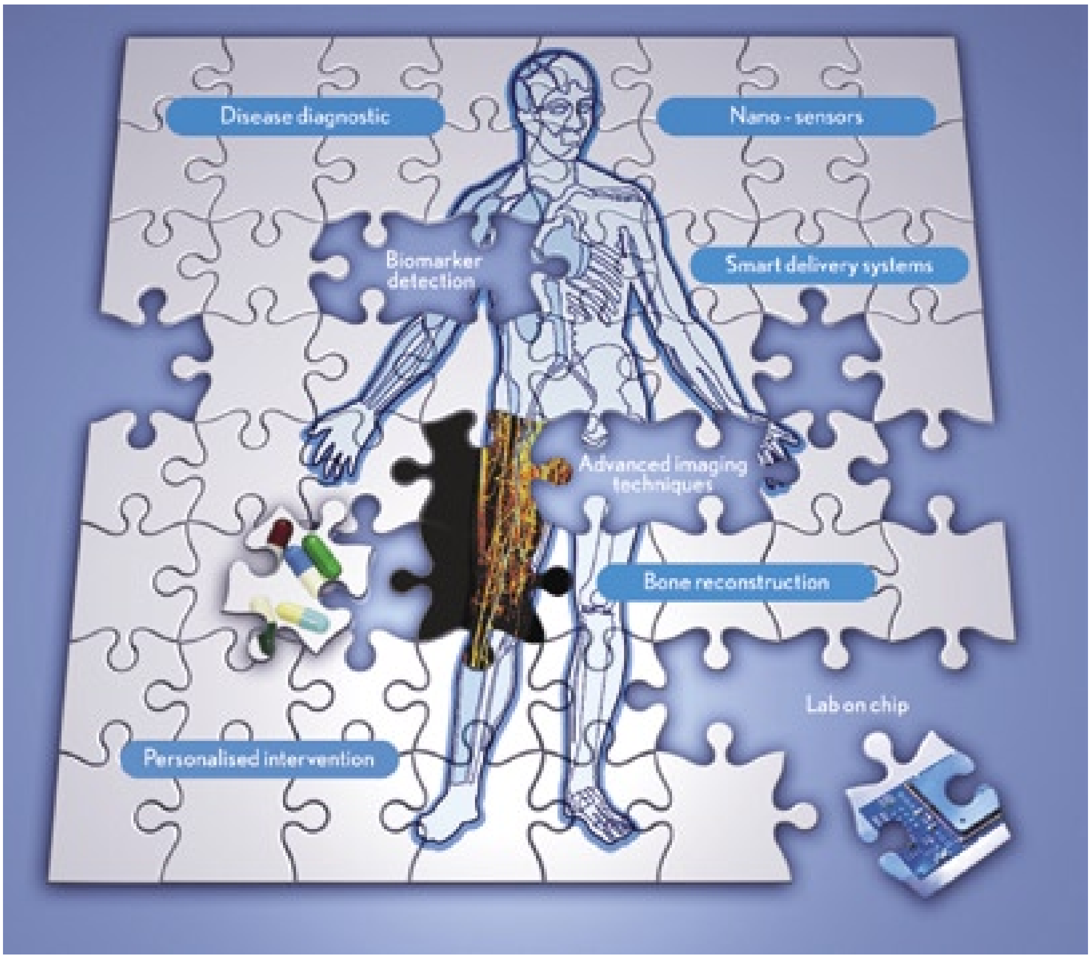
Novel drugs using nanomaterials will allow the formulation of special treatments to be optimised for specific needs. New functionalities at the molecular level will allow for the development of intelligent drugs which are better distributed in the body to target affected areas; are more stable in the human environment; and can be released along biological rhythms, thereby better responding to the needs of the patient.

A new generation of biotechnological antibiotics and antibodies will revolutionise the treatment of diseases. Enzymes which can selectively produce desired drugs with specific characteristics, replacing today's synthetic, less flexible substances, will enable the economical production of complex drugs to fight tenacious diseases.

While current applications in the biomedical sector focus on the development of synthetic materials for medical use, such as implants, soon the fundamental understanding of the interactions of artificial materials with biological interfaces should result in the development of biocompatible materials. These could be used for bone reconstruction, tissue engineering and increased efficiency of nutrients (vitamins, minerals, essential amino acids). Biomaterials with properties that protect transplanted cells from the immune system, avoiding the use of immunosuppressants, could be foreseen.

Overall, advances in sustainable chemistry can transform the medical intervention, improving diagnosis and treatment but also reducing costs and improving accessibility for patients.

Figure 3.6: Personalised healthcare.



The SusChem Strategic Research Agenda is an ambitious plan that will require significant funding in order to be successfully implemented. Different funding sources including EU framework programmes, national and regional initiatives as well as private sector spending will be needed.

Requirements

1 Budget

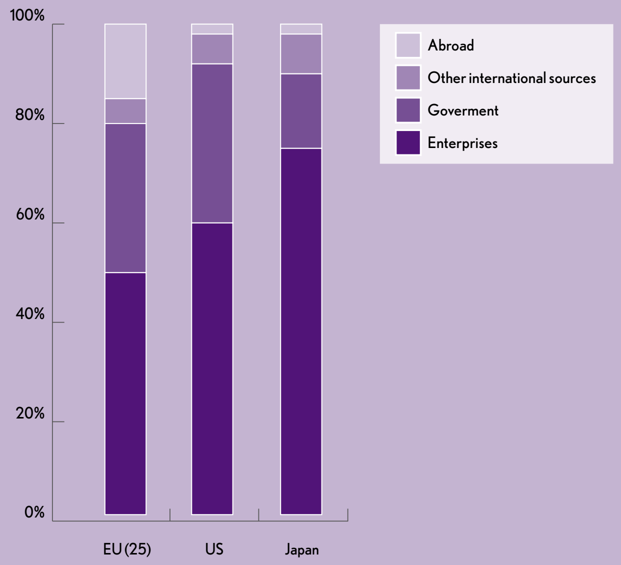
Creating knowledge and leveraging knowledge and innovation for growth is at the heart of the European effort to reinvigorate the Lisbon Agenda. Europe's knowledge, diversity and creativity are the key factors for creating a competitive advantage. Investing in research is therefore a necessity for Europe and it is vitally important to make sufficient financial resources available to be able to meet these goals. At the European Summit in Barcelona, in 2002, European Heads of State and Government set the goal of increasing Europe's overall level of investment in research to 3% of GDP by 2010, one third of which was to be funded by the public sector.

Despite this political commitment, total R&D expenditure as a percentage of GDP in the EU(25) remained almost stagnant in 2003, at 1.9%, lagging well behind the United States' 2.6% and Japan's 3.2%. Furthermore, the growth rate of R&D funding is very low compared to the emerging regions of the world (see Figure 4.1). From an industry point of view, the current focus on financial performance, frequent restructuring, increasing regulatory costs and a lack of well-trained human resources and dynamic markets are limiting R&D spending. Hence, the business sector financed 56% of the total EU(25) R&D intensity in 2002, while the respective figures in the US and Japan were 63% and 74% (see Figure 4.2).

The total R&D spending in Europe reached approximately €190 billion in 2003 compared to almost €250 billion in the US and €120 billion in Japan. The chemical industry itself (excluding pharmaceuticals) spent around €10 billion in Europe compared to €8 billion in the US and €5 billion in Japan.

Figure 4.1: Comparison of total R&D expenditure and average annual growth rates (2000-2003)[14].

Figure 4.2: Sources of funding 2002.



Biotechnology is used as one example to examine the worldwide differences in R&D funding. The United States sees the development of industrial biotechnology as a key strategic objective which has been backed by an impressive spend on research and development. Starting with a focus on interdisciplinary research and applied R&D, the programme now includes a range of public-private partnerships and large-scale demonstration projects. In 2003, the US Government spent nearly €420 million on industrial biotechnology research and demonstration projects. It also supports market development via a range of incentives.

The Japanese were amongst the earliest adopters of industrial biotechnology. Running up to 2007, Japan aims to double its funding of biotechnology research and triple the number of researchers involved. A significant proportion of this will be directed towards industrial biotechnology. Current funding covers projects for more than €54 million, including €20 million for the commercialisation of new products.

Another example for the strong competition with other regions of the world is nanotechnology. The National Nanotechnology Initiative (NNI) is a US federal R&D programme established to coordinate the multi-agency efforts in nanoscale science, engineering and technology. In 2004, the funding through the NNI amounted to €850 million with an expected increase to almost €1 billion in 2005. About 65% of NNI funding supports academic research, but a substantial portion promotes partnerships between researchers and private enterprise in order to leverage public investment. Collaboration between federally funded researchers and private industry has been identified by the NNI as critical for technology transfer and the commercialisation of nanotechnology. Public sources contributed nearly another €1.7 billion.

The total nanotechnology R&D spending in Europe reached approximately €2 billion in 2004 (with only €370 million from the EU) compared to the almost €3 billion in the US and €2.3 billion in Japan. Parts of these funds were used for R&D on nanomaterials and, hence, are relevant to materials technology.

SusChem

The SusChem Strategic Research Agenda is an ambitious plan that will require significant funding in order to be successfully implemented. Different funding sources including EU framework programmes, national and regional initiatives as well as private sector spending need to be accessed. This requires a high level of commitment from both, public bodies and private enterprises. The SusChem SRA offers a unique opportunity to focus the European spending on chemical R&D towards the most promising areas regarding their impact on the overall goal of sustainability and a high level of competitiveness. In order not to lose ground Europe needs to do as good as or even better than its competitors on the world market. This is especially true for research spending. Possible new funding mechanisms, new ideas and required changes in the framework conditions for research and innovation, will be presented in the forthcoming SusChem Implementation Action Plan.

The estimated resources needed for the SusChem SRA amount to approximately **€5.5 billion per year**. The required budget for the technology part of this figure was estimated based on the added value due to innovative process design for the overall industry production. The materials part (from the materials technology and the industrial biotechnology section) is based on the estimated future volume of the world market in SusChem-related areas and the necessary R&D spending to access new markets (between 2 and 5% depending on the maturity of the different markets). In a next step, an assumption was made regarding the share relevant to the EU and SusChem. The European chemical industry currently has a share of approximately 30% of the world chemicals market. SusChem covers approximately one third of all R&D areas in the chemical industry.

According to the Barcelona Summit, one third of this funding should come from public sources. SusChem thus requires **€1.8 billion per year** in EU and Member States funding.

The current overall EU contribution to public research funding in Europe is close to 5% but could and should reach up to 10% in the future. However, the EU contribution to SusChem needs to be well beyond this mark due to several reasons, such as: SusChem focuses on topics of European scope most often requiring the bundling of European knowledge; the importance of innovation in chemistry for the overall economy; the impact of the SusChem SRA on sustainable development in Europe; the move towards new innovative technologies that are key to achieving the Lisbon goals (nanotechnology and biotechnology); and the importance for Europe to sustain the current world lead of the chemical industry. Hence, the contribution from FP7 to the research presented in the SusChem SRA should be in the order of €1 billion per year. This is a reasonable share compared to the €10 billion spent by the chemical industry itself on all R&D topics. The requested budget is similar in magnitude to that of the US and Japan.

The emerging field of Industrial Biotechnology is increasingly impacting the chemical sector. It enables both the use of renewable resources and the efficient conversion of conventional raw materials using biotechnological processes. Industrial Biotechnology allows the production of a wide variety of chemical substances, many of which cannot be made by synthetic routes.

Industrial Biotechnology

1 Introduction

Industrial biotechnology, alternatively known as white biotechnology, is the modern use and application of biotechnology for the sustainable processing and production of chemicals, materials and fuels. Biotechnology uses enzymes and microorganisms to make products in sectors such as fine and bulk chemicals, pharmaceuticals, food and feed, paper and pulp, textiles, energy, materials and polymers.

Mankind has benefited from biotechnology for a long time, but with the advance of new technologies and much deeper understanding of cell metabolism and materials science, new opportunities have emerged and have been identified. A renewed interest in sustainable solutions to industrial processes has also contributed to biotechnology's recent popularity. Modern industrial biotechnology is therefore a relatively new discipline, with major areas of knowledge still to be explored. This presents a bottleneck to greater exploitation, but also offers a tremendous opportunity for further research. As a first step on the road to increased industrial use of the biological sciences, a strategic research agenda covering both basic and applied science is needed. Both are essential: basic science to develop the fundamental knowledge base, and applied science to use this knowledge to introduce innovative products and processes.

Vision

- Increasing numbers of chemicals and materials will be produced using biotechnology in one or more of the processing steps. Biotechnological processes will be used to produce chemicals and materials not accessible by conventional means or in a more efficient way.
- Biotechnology will allow increasingly eco-efficient use of renewable resources as raw materials for industry.
- Industrial biotechnology will enable a range of industries to manufacture products in an economically and environmentally sustainable way.
- Biomass-derived energy based on biotechnology will deliver an increasing amount of our energy needs.
- Green biotechnology will make a substantial contribution to the efficient production of raw materials.
- European industry will be innovative and competitive, with sustained cooperation and support between the research community, industry, agriculture and society.

Business objectives

- The development and production of novel, innovative products and processes in a cost- and eco-efficient manner using increasingly renewable raw materials.
- The discovery and optimisation of strains and biocatalysts.

In general, most of the industrial biotech processes developed so far use the most effective and convenient biocatalytic form, which is a whole microorganism. However this does not exclude the use of higher organisms, or the use of isolated enzymes, since the latter can easily be combined with chemical catalysts. The first aspect deals with the search for the best possible biocatalyst, with improved or totally new functionalities. In all cases the main driver is the cost- and eco-efficient production of the desired compounds by:

- Developing the best biological catalyst for a specific function or process.
- Creating the best possible environment for the catalyst to perform in.
- Separation, purification and further chemical conversion of the desired products from the bioprocess.

Another important part of industrial biotechnology deals with the containment system or bioreactor within which the catalysts must function. Here the combined knowledge of the scientist and the bioprocess engineer interact, providing the design and instrumentation for the maintenance and control of physiochemical environment such as temperature, aeration, pH, etc., thus allowing for the optimum expression of the biological properties of the catalyst.

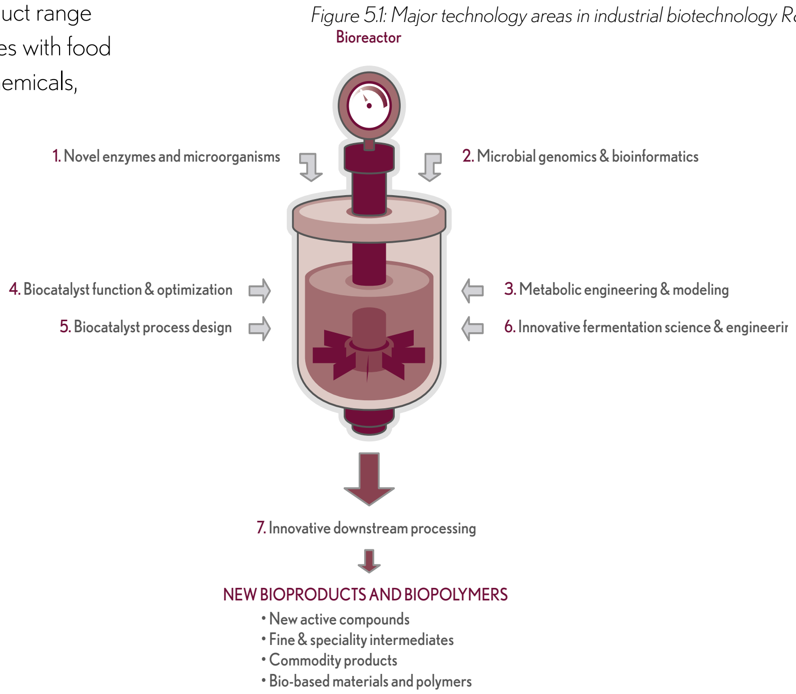
The third aspect, the downstream processing, is a technically difficult and expensive procedure. Downstream processing is primarily concerned with the initial separation of the bioreactor medium into a liquid phase and a solid phase, and subsequent separation, concentration and purification of the product. In addition, it includes the further chemical conversion of the (fermentation) product to yield the final desired compound. Chemical engineering principles play a vital role here in terms of design and operation of the separation systems. Improvements in downstream processing will benefit the overall efficiency and cost of processes and will make the biotechnology-based processes competitive compared to the conventional chemical processes.

These technical aspects have to be tailored with regard to the products, which are envisaged. The product range starts with biofuels and bulk chemicals, continues with food and feed additives, pharmaceuticals and fine chemicals, auxiliary materials for different industrial areas and ends up with biomaterials, surface coatings and nanoparticles. Depending on the case, the adequate technologies have to be selected.

Following thorough analysis by the main stakeholders, seven major technology areas were identified:

- Novel enzymes and microorganisms.
- Microbial genomics and bioinformatics.
- Metabolic engineering and modelling.
- Biocatalyst function and optimisation.
- Biocatalytic process design.
- Innovative fermentation science and engineering.
- Innovative downstream processing.

Figure 5.1: Major technology areas in industrial biotechnology R&D.



2 Research Areas

Novel enzymes and microorganisms

Scope

Industrial biotechnology is continuously looking for novel microorganisms and enzymes. The diversity of microorganisms, the molecules they contain and the processes they perform are truly immense. These enzymes and microorganisms can be found in almost all ecosystems. By modifying (tailoring) the DNA from these organisms, it is possible to optimise these processes and adapt them for use in industry. Culturing of the samples can, for instance, lead to **isolation of novel extremophiles** from specific sites.

The recognition that most microorganisms in the environment cannot be cultured by standard methods stimulated the development of **metagenomics**. Due to the relative ineffectiveness of standard laboratory culture techniques, the potential wealth of biological resources in nature is still relatively unknown, and uncharacterised. Metagenomics represents a powerful tool to access the abounding biodiversity of native environmental samples. The valuable property of metagenomics is that it provides the capacity to characterise effectively the genetic diversity present in samples regardless of the availability of laboratory culturing techniques. Information from metagenomic libraries has the ability to enrich the knowledge and applications of many aspects of industry.

New **high throughput** screening technologies to develop libraries on cloned organisms and to screen expressed target genes is another essential technology. Using robotics, specific predictive tests have to be developed to narrow the field of candidates to those genes that with a high degree of certainty can produce the desired protein when transferred into a host microorganism.

Research priorities

In the area of biomass and biofuels, attention should focus on converting and/or fractioning EU biomass feedstock by:

- Development of robust fermentation microbes, which are resistant to toxic compounds in raw materials, capable of utilising all sugars and to simplify and improve the effectiveness of the fermentation process for ethanol and other biofuels.
- Identification and development of innovative cocktails containing novel enzymes and microorganisms which are tailored to convert biomass drawn from EU sources (i.e. wheat straw, grasses, woodchips, sugar beet pulp, etc.) into fermentable substrates.
- Development of new processes through the combination of physical, chemical and enzymatic/microbial to convert biomass fractions such as lignin by enzymes and microorganisms to produce aromatics molecules for the industry.
- Valorisation of by-products of pulp factories for biofuel production.

In the area of bioprocesses and bioproducts, specific attention should be placed on:

- The search for novel enzymes and microorganisms from specific or extreme environments (extremophiles), whether by direct isolation or by metagenomics, to create an expanding range of biological catalysts for industrial use.
- The implementation of new easy and fast tools and technologies to discover functionality and properties of (new) enzymes (high throughput screening technologies, microliter/nanoliter scale, single molecule detection systems, systems to monitor enantioselective reactions).
- The development of improved, more intelligent, target-oriented screening technologies.
- New products or intermediates from biotransformation.
- New technologies to make more organisms amenable for metabolic engineering.

Highlights

- Expansion of the range of biological processes (new or improved microbes and enzymes) for industrial use.
- Discovery of new functions and properties of enzymes via new tools and technologies.

Key enablers, linkages and constraints

Europe produces around 70% of the world enzyme production and research in that field is well established and dynamic. However, industrial biotechnology requires more than ever new microorganisms and enzymes to use in industrial processes.

As the principal limits of the enzymes are their price and their industrial availability, finding the most appropriate microorganisms and enzymes are key points for the economic viability of new bioprocesses and bioproducts. The diversity of microorganisms, the molecules they contain and the processes they perform are truly immense. These enzymes and microorganisms can be found in almost all ecosystems.

The study of extremophiles, as well as marine and fresh water organisms, might be new sources in the search for novel enzymes for industrial use. However, most microorganisms cannot be cultured by standard methods and specific techniques are needed to unveil their genetic potential. Last but not least efficient screening technologies are crucial to detect genes of potential industrial interest.

Microbial genomics and bioinformatics

Scope

The key to understanding the activities of microorganisms lies in a better understanding of their genetics. With good genome mapping, the identification of desirable metabolic pathways and the adaptation to manufacturing processes would be accelerated. Recent advances in molecular biology and the equipment available for research in this field have allowed for the increasingly rapid sequencing of large portions of the genomes of several species. This deluge of information has necessitated the careful storage, organisation and indexing of sequence information. Information science has been applied to biology to produce the field called **bioinformatics**. While the storage and organisation of millions of nucleotides is far from trivial, designing a database and developing an interface whereby researchers can both access existing information and submit new entries is only in its infancy.

The microbial genome sequencing programmes have identified huge numbers of microbial genes, including many genes of unknown function and many genes encoding potentially useful proteins for industrial biotechnology. The genome sequencing activities are continuing at an ever-faster pace. A similarly rapid accumulation of large datasets is taking place for other genomic-scale activities, such as micro-array transcriptome expression analysis, proteome analysis, protein interactome analysis, etc.

These genomic methods have been exceptionally powerful in providing huge numbers of candidate genes for further experimental analysis. However, the latter proceeds much more slowly and an ever-widening gap is occurring between the accumulation of genomic information and its experimental evaluation and practical exploitation. Hence, there is an acute shortage of methods able to identify relevant genes and relevant information in the wealth of genomic information available today.

Research priorities

Functional microbial genomics

Functional microbial genomics lies at the heart of designing and studying future industrial bioprocesses. Broadly speaking, it will alter the perception of bioprocess design in two fundamental ways:

- It will dramatically expand the available genomic space that can serve as a source for understanding of fundamental microbial properties, such as gene functions and regulatory modules and as a source for novel or modified activities.
- It will form the intellectual basis of a future model-based, rational view of cellular design that is poised to improve the future biocatalyst design efforts by orders of magnitude.

Novel genes of given function

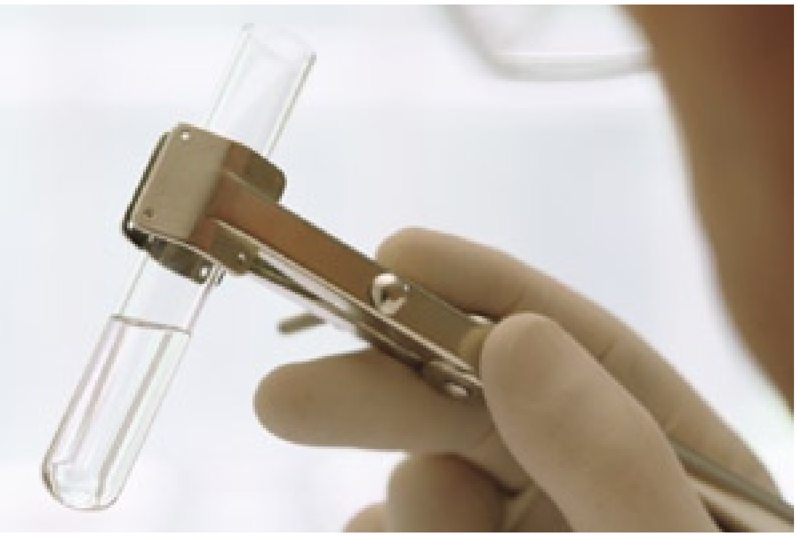
The explosion of microbial sequencing projects is opening up a huge reservoir of novel catalysts as well as unique *in-silico* resources for studying the genetic fundamentals of strain design and evolutionary history. This resource provides direct access to multiple variants of already identified functions that can serve as input for shuffling experiments, as functional equivalents under different conditions (such as genes from hyperthermophiles), or as input for the design of multi-domain enzymes. Acquiring genes for combinatorial biocatalysis or pathway design will become a matter of simply selecting appropriate algorithms to search a permanently expanding genomic space. Combined with the concomitantly improving ability to synthesise artificial genes for ever-larger DNA-segments, the assembly of artificial but suitably designed pathways for the selected production host should be dramatically facilitated.

Bioinformatics

Considering the large amount of data that are generated throughout the various "-omics" projects, one important future role of bioinformatics is the automatic data mining of large information sets, its automatic interpretation, and its proper visual representation to the user. Furthermore, the interpretation would need to be qualified by integrating other available data from the triplet proteome/transciptome/metabolome and observations from the literature. Such levels of integration are essentially currently unavailable. In addition, there is a need to refine the statistical methods that are applied to data analysis in order to improve knowledge extraction from massive data loads. Ultimately, the goal of bioinformatics will be to abstract knowledge and principles from large-scale data to present a complete representation of the cell and the organism, and to predict computationally systems of higher complexity, such as the interaction networks in cellular processes and the phenotypes of whole organisms.

Clarifying the function of unknown genes

The rational and efficient study of genes with unknown function through targeted and system-level gene disruption and over-expression studies, will lead to a more complete understanding of the available industrial biotechnology model organisms. This will also require novel methods to assess the behaviour of the resulting mutant strains beyond the digital statement of growth/no growth. Furthermore, advancing the ability to integrate the context of a given DNA segment, inspired by a wealth of possible ways of realisation from the already sampled genomic space, into the annotation of genes, will also improve the functional assignments.

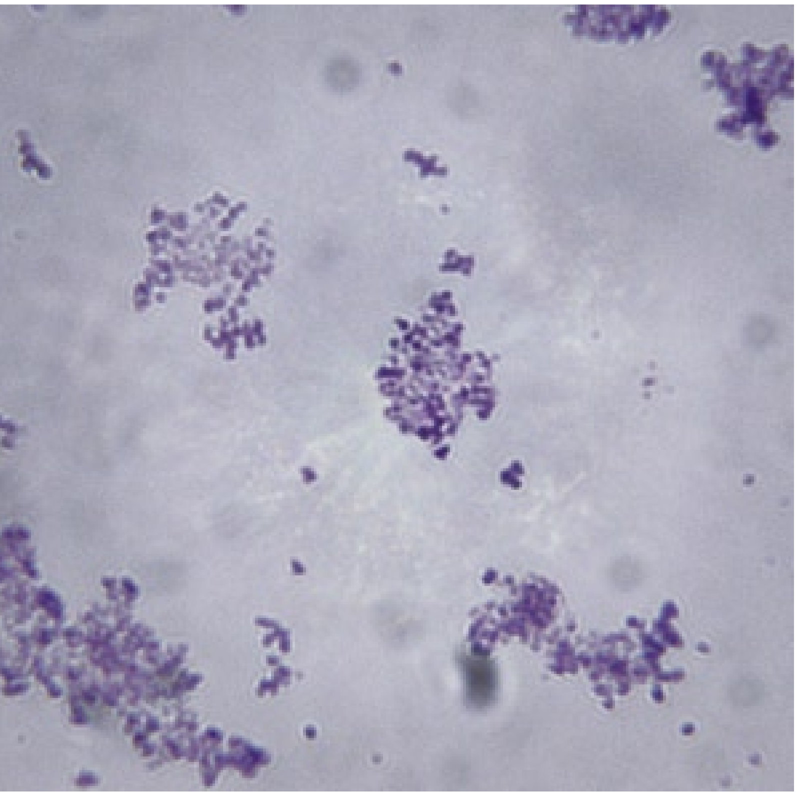


Advancing the understanding of more complex traits

Beyond the gene-level, drafting from a large genomic space will also allow much more profound delineation of the structure of more complex traits that are important to industrial biotechnology, such as flavour formation and the involved pathways, stress responses, natural product synthetic routes, etc. Finally, advances in comparative genomics will reveal the molecular mechanisms of how evolution led to novel enzymes, cluster, and even strain architectures and this will provide the basic principles that are needed when considering the design of suitable strains for biotechnological processes.

Activities building upon genomics – systems biotechnology

Next to the large gain in knowledge relevant to industrial biotechnology, genomics will form the basis of rational strain design efforts where the acquired novel insights are translated into highly efficient industrial biocatalysts. A genomic sequence is the reference point for any comprehensive subsequent, system-level analysis technology such as transcriptomics, proteomics, or metabolomics. Several key questions with respect to systems biotechnology need to be addressed in future research efforts that will require the interplay of all four of these technologies, such as a strain's physiology under the stresses that occur over the complete cycle of a production process. Drawing on the emerging resources of the systems biology community, industrial biotechnology needs to complement the missing, more process-specific elements, such as behaviour under intensive production conditions, the impact of rational rearrangements of large parts of an organism's genome, the combination of novel traits (solvent tolerance, stress resistance, high volumetric productivity, etc.) in one organism, and apply this body of knowledge to the design of highly effective production strains.



Minimal and artificial microorganisms – synthetic biology

Minimal, or even totally artificial microorganisms that can be used for microbial production processes will have significant advantages in industrial biotechnology. Such so-far hypothetical microorganisms could be derived from natural microorganisms with a minimal set of genes (minimal microorganisms), or could be totally synthetically generated using a given set of essential genes (synthetic microorganisms). As these organisms would possess a relatively simple metabolism and are very well understood and characterised, they would provide excellent prospects to be used as simple and efficient production organisms that can be easily modified and reprogrammed for production purposes in industrial biotechnology. Whereas the target is ambitious, its realisation is realistic and thus constitutes an excellent topic for a European-wide research effort that would cover nearly all science areas in industrial biotechnology.

Key enablers, linkages and constraints

Bioinformatics is already the working horse of systems biology, covering activities from automated genome annotations to the integration of disparate datasets from different system-level activities. These activities will have to be extended and intensified as the rate of data generation has increased to unprecedented levels, and linked to chemical databases such as Pubchem in the USA or KEGG in Japan.

Of particular importance to industrial biotechnology is the reconstruction of metabolic pathways from annotated genome sequences, also taking into consideration "accessory", context-sensitive information such as clustering of genes on the chromosome, protein fusion events, occurrence of profiles or signatures, and shared regulatory site to infer functional coupling of proteins involved in related cellular processes (as one pathway). In this way, rapid assessment of the metabolic capabilities of a specific strain and its immediate implications for process design would become rapidly available. This needs to be complemented by the development of proper algorithms to evaluate underdetermined systems. Where possible, this should also include known regulatory mechanisms, extracted from "-omics" experiments as well as from literature. This is a sine-qua-non prerequisite to the integration of data from different sources such as transcriptomics, metabolomics, proteomics, etc.

Highlights

- Increasing the availability and usability of genomic information through functional genomics, systems biotechnology, bioinformatics and synthetic biology.
- Improving the understanding of microbial biology, specifically for industrially interesting traits or pathways.

Metabolic engineering and modelling

Scope

Metabolic engineering is the improvement of cellular activities by manipulation of enzymatic transports and regulatory functions of the cell, typically using recombinant DNA technology.

This can for example be achieved via:

- Introduction of novel, non-native enzymes (e.g. from extremophiles) in an "optimal" microorganism, which has desirable properties with respect to its specific growth rate, genome, stability, process efficiency, growth requirements, etc., but which is a non-native producer of a certain metabolite. The product range of a popular production strain can thus be enlarged.
- Optimisation of microbial metabolism via manipulation of enzyme levels. Enzyme levels can be altered to redirect the metabolic flux towards a particular metabolite. This entails more than the use of knock-out or over-expression mutants. Nowadays the focus is shifting from massive over-expression and/or respectively inactivation of genes, towards fine tuning.

Research priorities

Molecular aspects under industrial conditions - systems biotechnology
The combination of genomics techniques with evolutionary engineering (selection of mutants equipped with new, better and more enzymes) must be exploited. High throughput screening of mutants is required to shorten the development phase of a new process or product. Gaps in the knowledge on the regulatory network of cells via protein-protein interactions, protein-DNA interactions etc. must be filled. This also holds for product export from cells and metabolic compartimentation in eukaryotic cell factories. These and other aspects of cellular regulation should be put into mathematical models. Crucial in this respect is that the information about cellular function should be obtained for conditions prevailing in industrial processes which involve stress, slow growth, fluctuations in nutrient concentrations, mixed substrate utilisation (such as mixtures of D-glucose, D-xylose and L-arabinose, originating from biomass hydrolysis), product formation under "zero growth conditions", kinetics of membrane transport at the extreme conditions in industrial bioreactors, product inhabitation in relation to product recovery, etc.

Industrially relevant products by metabolic engineering
Advanced metabolic engineering research for the efficient production of bioethanol, biomaterials and bulk chemicals, and also of specialties including enantiopure molecules, is required as well as research on the design and invention of new pathways and/or networks with a focus on new non-natural products, and on the extension of the range of industrial microbial production hosts.

Modelling of microbial metabolism
Mathematical modelling of microbial metabolism, directed towards both steady state and dynamic models, including the development of methodological tools, particularly for flux analysis and measurement of intracellular metabolites has to be developed. Special emphasis has to be given to relevant operating conditions.

Novel expression systems

Industrial biotechnology relies strongly on enzyme biocatalysts that are used in bulk applications such as conversion of the biomass carbohydrates into fermentable sugars or production of specialty chemicals by in vitro biocatalysis. The more new product opportunities there are, the larger will the need be for efficient production of a variety of different enzymes in large amounts. Most often, these enzymes will be derived from heterologous, even exotic organisms and need to be expressed in the current, or new, production hosts.

For protein production, research should focus on expression host technology by concentrating on basic problems like:

- Deepening the understanding of heterologous protein synthesis, expression, folding, modification and secretion.
- Deciphering secretion pathways and understanding how to manipulate them.
- Developing novel microbial hosts for optimal protein production.
- New synthetic pathways for new products not found in nature.
- Improved downstream processing and protein purification regimes.

Key enablers, linkages and constraints

As high product yields of microbial processes are *a conditio sine qua non* for their successful industrial application, metabolic engineering should be one of the spearheads of a policy that aims at encouraging industrial biotechnology, as it directly aims at increasing product yields or production efficiency. Knowledge and research in this area are well developed in Europe but specific attention needs to be paid to understand the metabolic interactions and regulatory mechanisms in the complex metabolic networks. Currently the optimisation of microbial metabolism to modify and test the synthesis pathways of interest for a particular compound is based on trial and error.

Metabolic models could help to speed up the process as a hypothesis can first be tested in silico to check whether a (set of) genetic modification(s) will yield the desired improvement.

Highlights

- Development of a better understanding of molecular aspects and microorganism metabolism under industrial conditions.
- Advanced metabolic engineering research for the efficient production of bioethanol, biomaterials, bulk chemicals and specialties including enantiopure molecules.
- Design and invention of new pathways and/or networks with a focus on new non-natural products.
- Mathematical modelling of microbial metabolism, directed towards both steady state and dynamic models.
- Novel expression systems focusing on protein expression.

Biocatalyst function and optimisation

Scope

Enzymes are capable of performing reactions with high conversion rates and specificity. Commercial exploitation of biocatalysts is of interest since biocatalytic processes can yield pure enantiomers with far fewer by-products. Techniques such as protein engineering (the design and construction of mutant proteins), gene shuffling and directed evolution techniques will enable the development of enzymes better suited to specific industrial environments. These tools will also allow the synthesis of new biocatalysts for completely novel applications such as the production of new to nature compounds.

Research priorities

Search for new biocatalysts

- Expand the range of enzymes from micro- and higher organisms from terrestrial, marine and fresh water origin for industrial applications.
- Take advantage of newly generated information on the biochemical pathways and enzymes utilised by marine and fresh water organisms to search for catalysts capable of novel chemical conversions, particularly C-C bond-forming reactions.
- Develop and apply high throughput screening (HTS) methods the for activity and (stereo)selectivity of enzyme and mutant libraries. Expand applicability of directed evolution methods (intelligent HTS methods, ultra-HTS, novel methods to create mutant libraries, etc.).
- Develop improved biocatalysts for the conversion of biomass.
- Discovery by metagenomics tools of new enzymatic activities for use in industry.

Optimisation of biocatalysts

- Designed evolution, rational design and combinations of thereof for the optimisation of biocatalysts (evolution of process stability, evolution of biosynthetic pathways for production purposes, optimisation of cell productivity).
- The in depth understanding of catalytic enzyme-substrate interactions to enable new enzyme applications or synthesis of new bioproducts.
- Create new functions into existing enzyme scaffolds (catalytic promiscuity).
- Develop cascades of bioconversions.
- Production of enantiopure components: developing tools to predict *in-silico* the proper enzymes with optimised properties.
- Highly biocompatible non-water miscible solvents or highly solvent tolerant biocatalysts are necessary to assure stable and high-performance integrated multiphase bioconversions.

Key enablers, linkages and constraints

Though enzymes are interesting industrially, as they can perform reactions with high conversion rates and specificity, natural biocatalysts are often not optimally suited for industrial application and therefore need to be modified for such a use. However protein engineering requires a multidisciplinary approach, involving recombinant DNA techniques, biochemical techniques, protein crystallography, and computer graphics (molecular modelling).

Highlights

- Expansion of the range of enzymes for industrial applications.
- Use of newly generated information on the biochemical pathways and enzymes to search for catalysts capable of novel chemical conversions.
- Optimisation of biocatalysts by directed evolution and/or rational design.
- Development of an in depth understanding of catalytic enzyme-substrate interactions to enable new enzyme applications or synthesis of new bioproducts.

Biocatalytic process design

Scope

Optimal **biocatalytic process design** will offer large efficiency gains in the production of major chemicals such as pharmaceuticals, food additives or antibiotics, as well as in the treatment of industrial and domestic emissions. Furthermore this technique is of particular interest to optimise the processes for the conversion of biomass into fuels and chemicals. Today, new designs result mainly from case-based reasoning. That is why promising process interactions are rarely discovered and exploited in industrial practice. Therefore, there is a strong need for systematic design technology for a quick and reliable selection of new high-performance process configurations.

Microreaction technology is particularly interesting as it opens completely new possibilities for chemical engineering, combinatorial chemistry, and biotechnology. Small, inexpensive, independent, and versatile devices ensure multiple simultaneous reactions; achieve maximum selectivity, minimum waste, and minimum investment. They lead to a better control of the process, safe manufacture and production on demand thus driving industry towards more efficient processes.

The improvement of the robustness of biocatalytic processes is a main issue and not only with respect to rendering renewable raw materials available in biorefineries. Techniques of biocatalyst immobilisation as well as the development of hybrid biocatalytic-chemical processes are of primary importance.

Research priorities

Integration of biocatalysts into industrial processes

- The optimisation of enzyme function by co-factor regeneration or design. Expand the applicability of co-factor-dependent enzymes: develop new recycling systems (enzymatic, chemical), change co-factor dependency, increased efficiency.
- The development and optimisation of biocatalysts for robust industrial processes (high temperature, medium engineering, solid to solid reactions, etc.). Enzymatic reactions in non-aqueous systems offer new possibilities for the biotechnological production of many useful chemicals using reactants that are not soluble in aqueous media. Enzymes in non-aqueous media and biocatalysts active at high concentration of substrates and products find applications in organic synthesis, chiral synthesis or resolution, modification of fats and oils, synthesis of polymers, etc.
- Direct integration of enzyme production and enzymatic transformation including downstream processing of target compounds in large-scale production plants for biofuels and bulk chemicals.
- Develop generic methods for immobilisation/ stabilisation.
- Develop water-based chemo-enzymatic routes.
- Integration of chemo- and biocatalysis.

Reduce the number of unit operations in biocatalytic processes

Multi-step bioreactions without isolation of intermediates need a purposeful design of the enzymes involved combined with new bioreactor process designs. Modelling of complex bioreaction systems with respect to kinetics, hydrodynamics, mass transfer and mixing will be necessary to identify optimum operation conditions.

Modular bioreactors

Modular bioreactors must be developed, because they represent useful tools for process development. They can be operated in a massively parallel way, thus shortening the time of experimentation. In addition, such microreactors may yield productivity enhancement and process intensification for process optimisation. The microscale approach has seldom been applied in the field of biocatalytic reaction systems, but it is of profound interest to address the identification of promising operation conditions, to characterise bioconversion systems, and to establish representative screening systems. This requires an understanding of the phenomena underlying mass transfer and mixing at microscale and concomitant modelling. The development and implementation of adequate engineering correlations must allow the effective translation of information gathered in micro- to large-scale processes. “Scale-up” and “scale-down” are the core issues.

Multiphase bioreactors

Multiphase bioreactors are of increasing interest as reactants with low water solubility are of particular importance in the chemical and pharmaceutical industry. Studies have to address the hydrodynamic characterisation of multiphase bioreactors, that is, liquid-liquid mass transfer in reactors operated in the presence of immobilised enzymes or whole cells. Integrated processes, characterised by *in-situ* product removal, most often represent multiphase reaction systems.

Biochips and microdevices for analytical purposes

Micro- and nanodevices have to be developed for chemical and biochemical analysis, including biochips for molecular and cellular detection and monitoring and for automated online monitoring of nutrients and metabolites in cultivation systems and process streams using optical and electrochemical detection systems. Europe has the largest industry for the production of biochips and it is important to build on this capacity.

Multi-enzyme and whole-cell bioconversion systems

Multi-enzyme systems, using multi-step reactions catalysed by cascades of enzymes have to be studied especially with respect to reaction systems, including steps requiring co-enzyme regeneration. Multi-step enzyme processes will also need to be investigated by spatially positioning or mixing together different enzymes within the reactors, as this methodology enables multi-step reactions to be conducted in such a way that it is not necessary to isolate intermediates. However, multi-enzyme reaction systems may frequently be developed on the basis of whole-cells. Metabolic engineering approaches will lead to novel whole-cell bioconversion systems.

Biocatalytic reaction engineering

Novel bioreactor and biocatalyst designs for more efficient and possibly continuous operation and for the development of novel processes have to be conceived. The redesigning of existing processes for better integration and reduced process steps and waste streams is required as well. Novel biosystems for existing chemical-synthesis processes are interesting goals as is the design of robust and economic processes with enhanced product quality and consistency in general.

Key enablers, linkages and constraints

Biological processes, which work well in the laboratory, need careful scale-up if they are to be equally effective on an industrial level. Good process engineering knowledge and skills are essential for this.

Highlights

- Integration of biocatalysts into industrial processes by optimising enzyme function, development of robust biocatalysts for industrial processes.
- Direct integration of enzyme production and enzymatic transformation including downstream processing of target compounds.
- Development of modular and multiphase bioreactors.
- Development of micro- and nanodevices for chemical and biochemical analysis, including biochips for molecular and cellular detection and monitoring, and for automated online monitoring of nutrients and metabolites.

Fermentation science and engineering

Scope

Fermentation engineering is at the heart of industrial biotechnology. Products and active ingredients are obtained by means of the cultivation of microorganisms. The discipline, therefore, is extremely important and has to benefit from novel developments in molecular biology, genome research, microbiology, biochemical engineering, process analyses, computer science and automatic control. Since the modern tools of bioinformatics and genome research will lead to more and more optimised high-performance strains of microorganisms fermentation engineering has to keep pace with this development.

Fermentation science and engineering constitute the workhorse of most bioprocess industries as well as of those industrial sectors making use of one or more bioprocessing steps in their flow sheets. This discipline is at the cross-section of life sciences, chemistry and chemical engineering and has as its focus the implementation of a cellular (prokaryotic or eukaryotic) culture within bioreactor systems on a production scale.

Research priorities

Microbial physiology

The application of specific stresses may sometimes be beneficial. Particular attention should be paid studying the physiology of microorganisms under conditions of extremely slow growth, because the normal fermentation process should yield a maximum of product and not of microbial biomass. Further improvements may result from developing processes working at extreme conditions of temperature and pH, or high substrates and product concentrations, as is crucial for efficient and economical fermentation.

Micro bioreactors for screening

Shortening of process development time is required. This includes, besides a knowledge-based approach, the development of highly parallel cultivation systems in order to be able to converge the development process rapidly into an optimised solution. This is why engineering of microreactors is entering biotechnology. This also means that highly parallel cultivation systems on small scale would have to be run under conditions met in industrial fermenters.

Measurement and control

A better automation of processes goes in parallel with better means of online measurement. Steam sterilisation still restricts the arsenal of analytical tools applied to fermentation processes. However, there are still a lot of interesting approaches, which have to be brought to the level of routine applications. Thus, fluorescence based techniques together with optical fibres are still very promising. Optical analyses combined with numerical image treatment may yield important analytical information.

Combination of systems biology and engineering

The highly parallel techniques of analysis known to end in "-omics" will rapidly increase in importance. Access to, for example, the transcriptome, proteome, fluxome, and metabolome, together with advances in systems biology, will have a dramatic influence on process development for processes of primary importance, although most of these techniques are still far from being applicable as routine methods. However, massive advances may only be obtained when interdisciplinary teams are formed and working together and are receiving feedback of knowledge from each step of process development. Such a strategy would help to avoid carrying out experiments under conditions far from those being expected under process conditions.

Fermentation engineering
Studies of the influence of fermentation conditions on the performance of microorganisms are of primary importance. Engineering tools should be used for designing strategies for process intensification. This includes the development of low-cost fermenters, alternative novel reactor concepts, advanced control strategies and the development of simulation tools for modelling fermentation processes on different scales. Although there has been quite some success in modelling fermentation processes on different scales, much more effort is needed until these tools may be applicable for routine process development. The development of continuous processes and reactors needing less maintenance may represent a strategy worth following. Closed-loop cycle with, for instance, recycling of microbial biomass should lead to optimal product yields. Process integration is an important issue as well.

Combination of energy production and fermentation/biocatalysis
Especially in the implementation of early fermentation or biocatalysis steps in the concept of a biorefinery (production of building blocks), an integration of energy production (e. g. heat) based on renewable resources (e. g. biogas plant) is of great importance. It is expected that these processes will need higher temperatures for the pre-treatment of the substrates. In addition, the biomass (up to 50% yield under aerobic conditions) produced during fermentation processes could be used for further energy production. Thus, new concepts for the integration of fermentation plants, biogas plants and block-type thermal power stations (BTTP) should be under investigation.

Key enablers, linkages and constraints

Although mature in comparison with emerging biotechnological fields such as genomics and metabolic engineering, fermentation science and engineering is profiting from advances in specific areas, including computer-aided design, process modelling and control. The need for flexibility within established bioprocess industries (antibiotic fermentations or food fermentations) dictates fairly standard bioreactor design (primarily stirred tanks and, to a lesser extent, bubble columns or airlift vessels) and mode of operation (mostly batch or cyclic fed-batch), whereas new and upcoming applications may require innovative reactor design and operating regime (fed-batch with adaptive profile feeding). Processes for new highly priced products could well justify the development of unconventional bioreactors and sophisticated process control schemes. This is an area with growth potential worthy of further investment in R&D.

The screening of media ingredients with quantifiable effects on the performance of a given bioprocess is exemplified by the current trend towards using synthetic media components and by the progressive recycling of agro-food waste streams into media for fermentations. This trend needs to be taken to its logical limit, with the implementation of zero-discharge guidelines. The issue of containment provisions regarding the potential discharge of GMOs should be taken into account. Therefore, massive advances may only be obtained when interdisciplinary teams are formed and working together and are receiving feedback of knowledge from each step of process development. Such a strategy would help to avoid of carrying out experiments under conditions far from those being expected under process conditions.

Highlights

- Development of engineering tools for designing strategies for process intensification, such as low-cost fermenters, alternative novel reactor concepts, advanced control strategies and simulation tools for modelling fermentation processes on different scales.
- Development of micro bioreactors for screening to shorten the process development time, considering conditions of large scale production.
- Studying the physiology of microorganisms under extreme conditions: pH and temperature, slow growth, high concentration of substrates and products.

Innovative downstream processing

Scope

So far, there has been less interest in downstream processing than in mass conversion technologies in industrial biotechnology. This lack of interest has resulted in a technology bottleneck in more traditional processes through a deficiency of specialised, high throughput apparatus and automation systems. However, because typically 50-70% of the total production cost in technological processes can be attributed to downstream processing, it is a very important part of the overall process. Designing an economically competitive and environmentally sustainable technological process means considering the downstream separation needed to capture the final product during the initial process design. It is key to take into account the overall processing requirements as early as possible in the development of a new industrial biotechnology process. As downstream processing is highly product specific, it is more difficult to develop generic methods and it is therefore an aspect often neglected in research programs. The specific requirements to obtain a workable and effective industrial process have to be included in the research program. Moreover to avoid classical pitfalls that are encountered in the scale-up of a lab process into an industrial process, it is important to recognise these from the beginning.

Research priorities

Achieving high efficiency at low costs means approaching the design of the bioprocess and downstream separations as a single, integrated process. In this approach, the bioreaction is regarded as one entity with both upstream and downstream unit operations.

Innovative downstream processing
Bioprocesses often suffer from a low volumetric productivity because reaction products can cause inhibitory or toxic effects on microorganisms, or biocatalysts, and/or the chemical equilibria are unfavourable for the desired products. The low productivity can be overcome if the products are removed from the medium as soon as they are formed by means of *in-situ* product removal or by innovative ways of downstream processing. Innovative downstream processing can also consist of the combinations of (hybrid) separation techniques, newly developed materials with high specificity/selectivity (like membranes, electrodes, ligands, adsorbents, extractants, resins, etc.) or modes of operation with unconventional conditions.

Research must concentrate on:

- Development of a toolbox of generic techniques (i.e. different techniques for different groups of compounds). With a well-balanced selection of techniques it will be possible to cover the majority of product recovery questions in bioconversions. A consortium of research groups and end users should conduct this kind of research. Every partner can use the toolbox produced to fine tune a technique or set of techniques to its own specific needs.
- The scale-down and parallelisation of multiphase bioreactors which is a prerequisite for a fast identification of suitable process conditions.
- Development of computer-aided design systems (with built-in models of the unit operations employed in biotechnological plants) to assist process engineers in optimising the design of innovative downstream processes.
- Development or improvement of continuous fermentation processes with new *in-situ* product removal techniques ("in-stream processing") with highly selective materials (membranes, resins, extractants, etc.).

Process integration

Process integration and intensification is another important topic, especially for biotechnological processes for lower-value higher-volume chemicals (the so-called commodity bioprocesses). It becomes necessary to maximise efficiency, and minimise costs and waste by-products to become economically viable compared to traditional approaches. Some aspects such as the choice of reagents used in downstream processing, the choice of a discontinuous or batch process, optimisation of energy consumption, and recycling of reagents or by-products are essential to improve the eco-efficiency of the process.

Research must concentrate on:

- Integration of downstream recovery and chemistry (in-broth chemistry) which will facilitate further conversion of fermentation products.
- Integration of downstream processing and bioprocess, saving water and energy and reducing waste.
- Minimising the waste stream (downstream as well as upstream).
- Developing sustainable production methods with no by-products.
- Saving water and energy during biomass extraction.

Key enablers, linkages and constraints

So far in industrial biotechnology there has been less interest in downstream processing than in mass conversion technologies. This lack of interest has resulted in a technology bottleneck in more traditional processes through a deficiency of specialised, high throughput apparatus and automation systems. Designing an economically competitive and environmentally sustainable technological process requires consideration of the downstream separation needed to capture the final product during the initial process design.

Highlights

- Development of innovative downstream processing techniques such as computer-aided design systems, and continuous fermentation processes with new *in-situ* product removal techniques.
- Development of a toolbox of generic technique (i.e. different techniques for different groups of compounds) to cover the majority of product recovery questions in bioconversions.
- Integration of downstream recovery and chemistry to facilitate the further conversion of fermentation products, minimising energy and water input as well as waste streams.

Tomorrow's society will require materials with increasing demands on properties and flexibility. The development of these innovative materials will enable new business creation. In addition to their new properties, these new materials will minimise the use of resources and limit environmental impact.

Materials Technology

Materials Technology

Definition of material science: *Generating new knowledge on high-performance materials for new products and processes; knowledge-based materials with tailored properties; more reliable design and simulation; higher complexity; environmental compatibility and environment preservation; integration of nanomolecular-macro levels in the chemical technology and materials processing industries; new nanomaterials, biomaterials and hybrid materials, including design and control of their processing.*

1 Introduction

As the 21st century unfolds, it is becoming more apparent that the next technological frontiers will be opened not through a better understanding and application of a particular material, but rather by understanding and optimising material combinations and their synergistic function, hence blurring the distinction between a material and a functional device comprised of distinct materials[15].

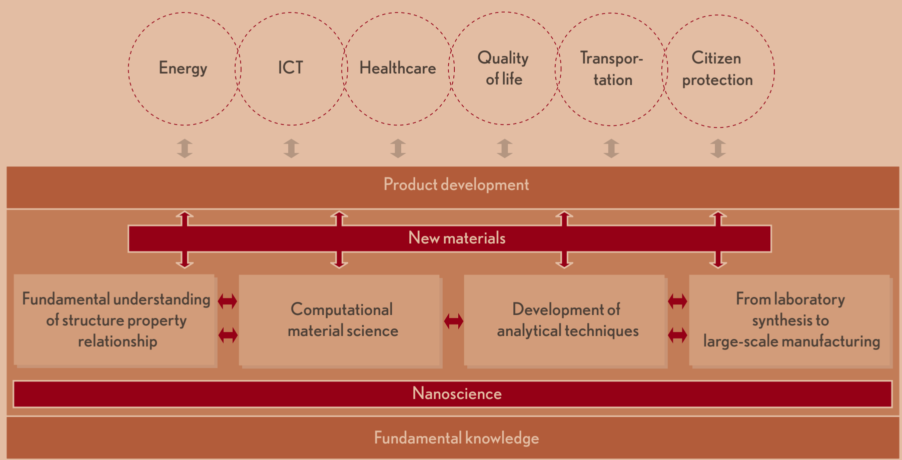
Discovery of new materials with tailored properties and the way to process them are the rate-limiting steps in new business development in many industries. The demands of tomorrow's technology translate directly into increasingly stringent demands on the chemicals and materials involved, e.g. their intrinsic properties, costs, processing and fabrication, benign health and environmental attributes and recyclability with focus on eco-efficiency.

Materials science deals with the design and manufacture of materials, an area in which chemistry plays the central role; there is also considerable overlap with the fields of chemical engineering, biotechnology and physics. Materials science has made substantial contributions to many fields including: modern plastics, paints, textiles and electronic materials; but there are greater opportunities and challenges for the future. Materials chemistry is vital for all areas of science and technology as well as for the needs of society in respect of energy, information and communications technology (ICT), healthcare, quality of life, transportation and citizen protection (see Figure 6.1).

Doing complete lifecycle analysis on newly developed products, and considering all the ecological as well as the socio-economic components, will help to ensure growth and employment in the European Economic Area (EEA). Furthermore, material science will play an important role in contributing to the solutions for some emerging societal needs and in increasing the quality of life of European citizens.

Converging with the various performance demands are a suite of new technologies and approaches that offer more rapid new materials discovery, better characterisation, more direct molecular-level control of their properties and more reliable design and simulation.

Figure 6.1: Structure for the Materials Technology section.



Vision

- To make Europe the world's leading supplier of advanced materials.
- Innovation in materials technology driven by societal needs and contributing to improved quality of life for European citizens.
- Accelerated identification of opportunities, in close cooperation with partner industries down the value chain, leading to materials with new and improved properties.
- The ability to rationally design materials with tailored macroscopic properties based on their molecular structure.
- Products based on integrated complex systems available by improving and combining the benefits of traditional materials and nanomaterials.
- Convergence of market demand and technology development creating many opportunities for new enterprises in the materials sector (e.g. SMEs).

The tasks of materials technology

The task is to provide guidelines for realising the goals and challenges set by the EU to address the societal needs of energy, healthcare, information and communications technology, quality of life, citizen protection and transportation (mobility).

Five research areas were identified which are discussed in further detail in this chapter:

- Fundamental understanding of structure property relationship.
- Computational material sciences.
- Development of analytical techniques.
- New production processes for the scale-up of laboratory synthesis for improved materials.
- Bio-based performance and nanocomposite materials. The chapter is concluded with a special focus section on nanotechnologies and nanosciences.

2 Research Areas

Fundamental understanding of structure property relationship

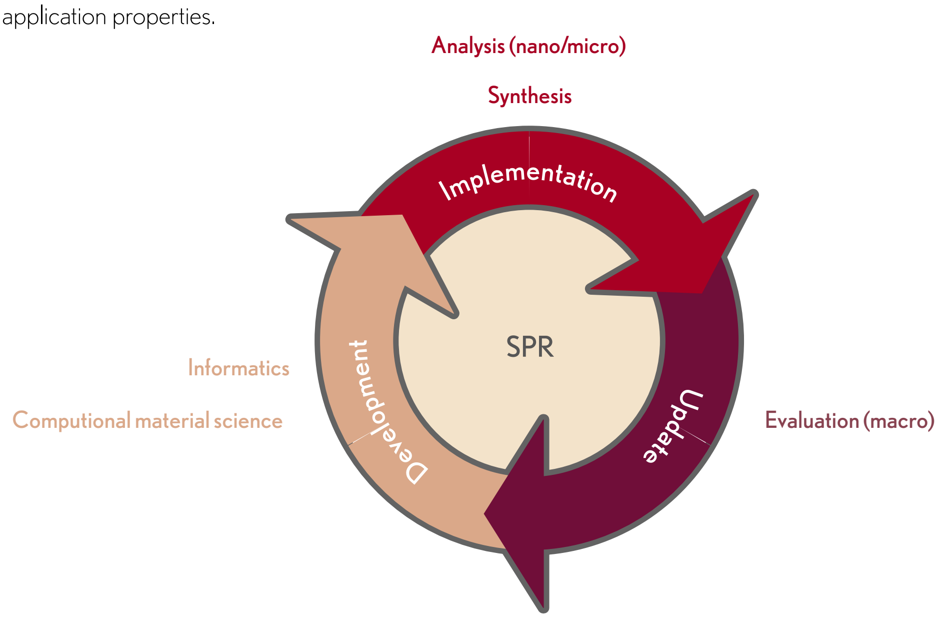
The control and understanding of the structure property relationships (SPR) of molecular systems is crucial for the intelligent processing of advanced materials. This is one of the unresolved problems in materials research, particularly in the development of innovative synthetic strategies and environmentally friendly chemical technologies. The SPR-based theoretical approach can provide guidance and permit the reduction of costly experimental work. It is also very important for optimum production and process design. Over the last decade, this approach has provided an increasingly important means of improving and optimising many kinds of materials from metals, ceramics and superconductors to bio- and smart materials used for specialist applications like microelectronics and bio-inspired catalytic systems (see Figure 6.2).

Scope

There is a pressing industrial need to understand better complex physical-chemical and biological phenomena relevant to the mastering and processing of multifunctional and eco-efficient materials, providing the basis for developing novel materials with predefined physical, chemical or biological characteristics. Industry and academia thrive in the field of connecting chemical structures with fundamental and application properties.

In many, albeit very specialised cases, the problems related to SPR had been solved successfully. Nevertheless, in Materials Science, the SPR-based approach has always been more qualitative, and efforts to gain a more generally applicable insight have collapsed due to the missing links to mathematics, high-throughput experimentation and the computation of complex data or the modelling of real materials. In all these disciplines, new features were developed which through integration should have opened new opportunities to make materials by design. Currently, modelling and simulation at the atomic and molecular levels can provide a basic understanding of structure property relationships among chemical, microstructure and material properties, and can give us a better "unbroken chain of knowledge": from fundamental research to applied research for materials. Breakthroughs will come not only from the new materials developed in this field but also from the new computational approaches.

Figure 6.2: The interaction cycle for structure property relationship.



Research priorities

Grand challenges that require theoretical and computational efforts include:

- The fundamental understanding of catalysis and the rational design of new catalysts.
- The fundamental understanding of interfaces and nanointerfaces.
- The fundamental understanding of formulations to achieve controlled functional properties.
- The development of innovative synthetic strategies and new chemical reactions.
- The development of polymer nanostructures used as nanoreactors for metal nanoparticle formation.
- The development of controlled surface-induced (template) co-polymerisation processes leading to various functional co-polymers (in particular, co-polymers capable of pattern recognition).
- Improved understanding of the effect of synthesis conditions, catalyst composition and structure on the chemical and material structure and composition.
- The understanding of growth kinetics, surface grafting and modification, polymorphs, etc.
- The design of advanced materials and composites (advanced high-strength/low-weight materials).
- The design of template nanoporous polymeric materials.

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The SPR-based approach is an intrinsically multidisciplinary field that implies intimate interconnection between computational materials science, informatics, analysis and chemical synthesis.

The priority categories of the SPR-based approach as applied to sustainable chemistry problems include:

- Informatics & computational materials science.
- Technology applications (related to chemistry and biology).
- Advanced chemical reactions and chemistry for new materials.
- Evaluation and assessment of theory.

Key enablers, linkages and constraints

New industrial processes and products that are based on a deep understanding of structure property relationship, providing better quality, durability, cost effectiveness, functionality, structural properties and improved performance, will be critical drivers of innovation in technologies, devices and systems, benefiting sustainable development and competitiveness through multi-sector application. However, to assure Europe's strong position in the technology market, the various actors need to be mobilised through leading edge RTD (research, technology & development) partnerships and long-term and high-risk research.

Highlights

- Describe the relationship between functionality and material properties by rationales.
- Integrate high throughput analysis and computational materials science.
- Accelerate the development of new material technologies through the efficient analysis of experimental data and modelling, and simulation.

Nanotechnology will:

- Provide an understanding of surface effects, providing a means of control.
- Help to understand the link between size-shape-phase and chemistry (internal and external).
- Help to determine the stability and safety of new nanoparticles in dry, wet and colloid forms.
- Provide an understanding of surface effects that may lead to exploitation of surface characteristics e.g. in catalysis, electrodes, sensors, and their interfaces with gases.
- Through an understanding of the special interfacial properties of nanoparticles, which have very high surface areas, allow their use in composites and also as coatings.

Computational material science

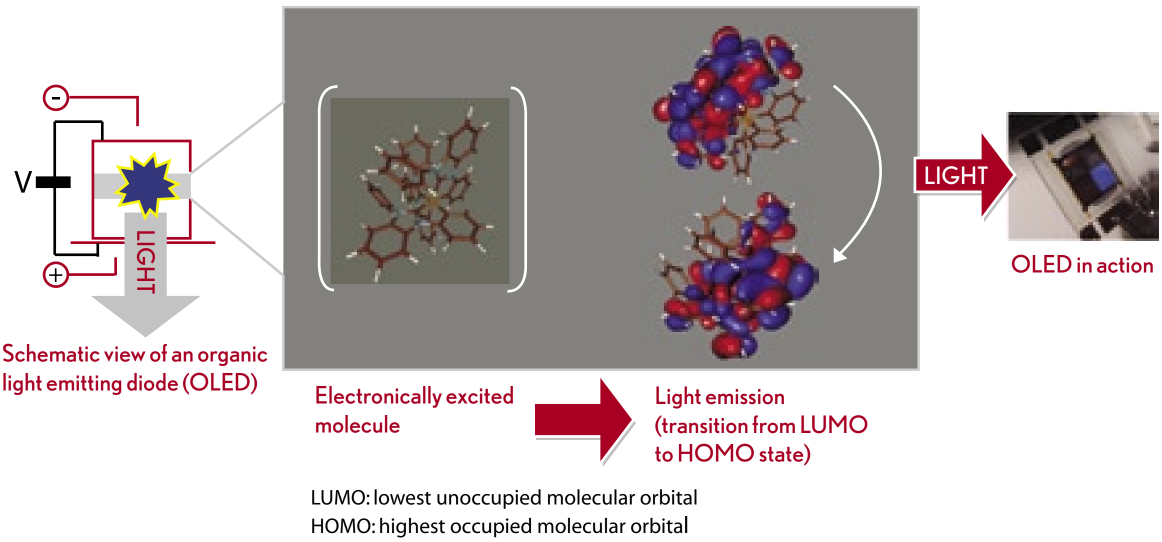
A major change in design and manufacturing during the past 50 years has been the growth of (computer) simulations as a design tool. There is enormous potential for modelling and simulation to impact on numerous important industrial and scientific problems involving the materials sciences, biotechnology and chemical technology. This opportunity lies in the ability to design, characterise, and optimise materials before beginning the expensive experimental processes of synthesis, characterisation, processing, assembly and testing. With reliable de novo simulations on real materials, industry could save enormously by cutting years off development cycles, while achieving designs that are more efficient. Moreover, such de novo design would allow efficient consideration of completely new materials as well as cost-efficient, flexible, clean and energy-efficient (bio)chemical processing with improved yields, reduced waste and maximum recycling.

Scope

Treating processes taking place on multiple length and time scales continues to challenge theorists. It is possible to identify two coupled forefront directions in modelling and simulation: the control of atomic and molecular interactions and processes at the quantum level (see example in Figure 6.3) and the treatment of ever more complex systems. An ultimate goal is the union of these two directions. The potential benefits of realising this long-term vision include the ability to enhance chemistry research and innovation, in particular in the areas of biotechnology, reaction and process design and materials science, thus leading to breakthrough chemical product and process innovations and support an increasingly sustainable, eco-efficient and competitive industry.

A central and basic challenge is clear: the need for the quantitative prediction of the properties of matter (both "soft" and "hard") is becoming more urgent, and the absence of that ability is increasingly a barrier to progress in modern industries ranging from molecular electronics to biotechnology. The primary fundamental challenge is to uncover the elusive connections in the hierarchy of time and length scales, and to unravel the complexity of interactions that govern the properties and performance of advanced materials. In terms of computational chemistry (CC), these challenges translate into a more specific requirement: the coupled atomistic-continuum modelling approach is one of the primary problems associated with hierarchical simulation of materials; namely, the accurate understanding of physical/chemical processes and behaviour from the quantum level, to nanoscale, to

Figure 6.3: Computational material science in the development of a blue OLED: Simulation of emission characteristics.



,mesoscale and beyond, so that phenomena captured in simulations can be applied to real complex systems without loss of intrinsic structural information.

Research priorities

- Development of new techniques and models aimed at bridging the length and time scales for more complex systems in computer modelling.
- Development of simulation methods for systems with specific interactions.
- Development of analytical techniques for materials research via computer modelling.
- Development of large-scale scientific applications software and new userfriendly interfaces for computational tools.
- Computational synthesis needs experimental growth, characterisation and modelling of nucleation, and growth as a function of chemistry, temperature, surface, catalyst and the resulting structure and composition.
- Computational materials properties needs experimental and model correlation of structure and composition with actual material properties.
- Since nanomaterials have a high surface to area ratio, significant research must be done into the impact of surface chemical state and functionalisation on properties of the isolated nanomaterials and when embedded in other materials.

A primary contribution from a materials simulation initiative would be to develop a capability to reliably predict the properties of real materials. To achieve this far-reaching goal one must be able to simulate realistically physical phenomena over a vast range of time and length scales. New hierarchical materials modelling approaches that span multiple length and time scales, and that couple quantum mechanical methods at the atomic scale to continuum defect modelling at the micron scale, have to be used in this area. The focal points of computational chemistry are:

- Accelerated discovery of new nanostructured and multifunctional performance materials.
- Connecting theory and simulation with experiment.

Key enablers, linkages and constraints

By its very nature, computational chemistry is an intrinsically multidisciplinary field that involves multiple length and time scales as well as the combination of types of materials and molecules that have been traditionally studied in separate sub-disciplines. This means that fundamental methods that were developed in separate contexts will have to be combined and new ones invented. This is the key reason why an alliance of investigators in computational chemistry with those in applied mathematics and computer science will be necessary for the success of theory, modelling and simulation. A new investment in theory, modelling and simulation should facilitate the formation of such alliances and teams comprising theorists, computational scientists, applied mathematicians and computer scientists.

Highlights

- Development of new computational tools to describe the fundamental material properties.
- Development of computational methods that bridge the length-time scales.
- Development of new empirical methods to describing mixing and diffusion effects.
- Development of new computational methods for formulations: nanocomposites, real interfaces and biological systems.

Nanotechnology will:

- Provide an understanding of effects between the 25 nm and 100 nm length scales, completing/rounding of the "entire" length scale.
- Provide an insight into the effects of Brownian motion (chaos effects), helping to develop products, which vary their properties over time and temperature.

Development of analytical techniques

One of the essential prerequisites for the development, manufacturing and commercialisation of any new material technology lies in the availability of techniques which allow for the characterisation of the physical, chemical or biological properties inherent to these materials, at any stage from exploratory work through to production process. Furthermore the behaviour of these materials under various chemical and physical conditions, their distribution within environmental domains (e.g. soil, water and air) and their interaction with the biosphere (e.g. human, etc.) need to be elucidated.

There exists to date a considerable ensemble of detection and characterisation methods, but these are limited in their scope of application. Keeping the key challenges in mind, the needs of the analytical chemist can be divided, loosely, into four categories:

- Single molecule/entity characterisation.
- High-volume throughput fast analysis.
- Analysis of nanomaterials.
- Analytical norms and standards.

Nanomaterials themselves can be very interesting as potential analytical tools, particularly if they provide sensitivity and selectivity towards a defined range of analytes. The focus lies in developing chemical sensors, which can be applied to both environmental tasks and industrial process control, and in medical treatment and disease detection. Both are key topics in increasing economical sustainability.

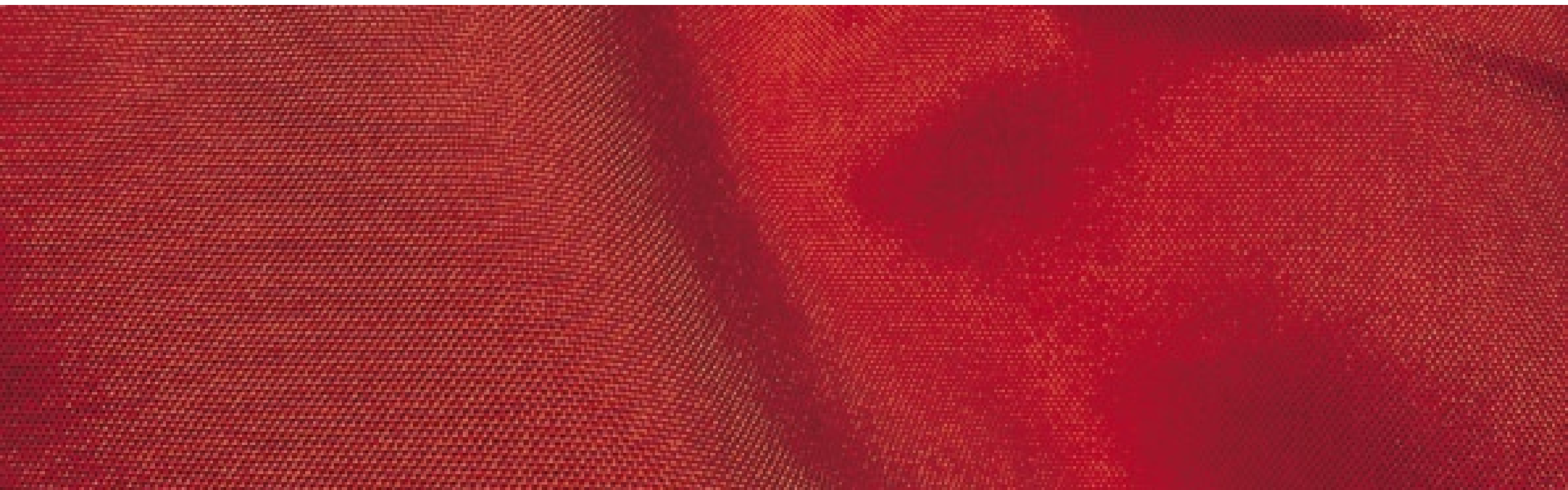
Scope

Extend the capabilities of current analysis methods to achieve nanoscale determinations of substances; to design and implement efficient high throughput mechanisms; develop common standards and to move forward towards "smart" production process and environmental hazard monitoring.

There are two main challenges, which need to be addressed within the next round of EU Framework Programme projects:

- To conclusively, efficiently and rapidly identify/ characterise any new material technology, and describe its inherent property, whether at the nano-, micro-, meso- or macro-scale.
- To assess the analytical ability of any new material in terms of its "recognising" properties, and its potential application for separation, detection or chemical sensing.

These are bold statements, but are reasonably achievable, when one considers how rapid the development in analytical methods has been in recent years. These developments need to be encouraged, as the analysis of materials lies at the heart of any process, whether it is for quality control or the elucidation of a new compound's structure.



Analytical chemistry provides an understanding of the nature of a material through the characterisation of its structure, the measurement of its physical parameters, and the observations of its interaction with other materials and/or environments. The information gleaned in this manner cannot only be used in the development of further new materials, but also in developing new-targeted analytical methodologies. Therefore those charged with the task of promoting advancement in analytical techniques should not only include academics specialising in analytical methods and small-medium-enterprises (SME) who provide analytical services and instruments, but also those researchers working at the frontier of new material technology research and agencies that are responsible for establishing norms and standards. Conceivably these parties could combine their input and expertise into the creation of analytical technique competence centres.

Europe has a strong position within these fields, as it hosts excellent academic research groups within the field, a strong chemical and microelectronic industry providing analytical tasks as well as novel transducer technologies and a range of SMEs that are actually willing and capable of bring chemical sensor systems to the market.

Research priorities

For the development of analytical techniques:

- Development of new single molecule/entity characterisation techniques.
- Development of new high-volume throughput, fast analysis techniques.
- Development of new instrumental methods for the analysis of emerging material technologies.
- Development of the ability to monitor at an atomic level the nucleation and growth of nanostructured materials, this is necessary to validate the models of synthesis, to predict structure and composition of the nanomaterials, including catalytic mechanisms.
- Provision of a framework for the promotion of the development of norms and standards.
- Development of reference materials.

For the development of devices (e.g. new business opportunities for SMEs, etc.):

- Development of portable analysis equipment.
- Extension of current instrumental methods to higher degrees of sensitivity and efficiency.
- Development, within continuous synthesis and analysis, of inline and online systems.
- Development of new efficient automated processes for sampling and analysis.
- Development of hybridised instrumental methods to facilitate rapid analysis.

For the use of nanomaterials for analytical purposes:

- Development of techniques for the analysis of nanomaterials.
- Development of techniques for the detection of nanomaterials.

Key enablers, linkages and constraints

The European community has a very strong chemical industry, with strong innovation skills and leading competences in various fields including nanotechnology, and it has a first class academic research community. Both industry and academia can become key enablers for sustainable chemistry, whereby measures have to be taken to close the communication gap between both parties. The European community furthermore needs to create a common quality control and standards organisation, with emphasis on the standardisation of nanotechnology analysis.

Highlights

- Pattern/cluster recognition systems for high-volume throughput analysis.
- Nanomaterials as self-sensors/analytes.
- Large scale efficient quality control (QC) of nanoscale structures (e.g. coatings).

- Nanotechnology is key to differentiate between analytical tests that may need to be conducted on nanomaterials and analytical tests that are based on the use of nanomaterials.
- Transfer of high-throughout screening techniques from the bio-world into the inorganic world is likely to transform the analytical methodology for inorganics and this transformation is dependent on nanomaterials as its basis.
- Similarly, combinatorial techniques from the bioworld are likely to lead to an understanding of novel material properties and useful applications based on evaluations at the nanoscale. Techniques are required to combine such methods and conventional inorganic processes.

From laboratory synthesis to large-scale manufacturing

Countless new materials, especially nanomaterials, have been synthesised in laboratories worldwide, opening up a broad variety of new applications. Many of the new, valuable products, which improve every day life, would not work without these materials. All too often, however, new exciting materials never leave the laboratories because the road from the fundamentals of science through to end-systems production was too long and complicated.

It is a major challenge, therefore, to implement the use of nanomaterials and nanotechnologies in real world products. In order to create these high-value products, academia, materials producers and final system integrators have to work together in close collaborations. The much stressed European paradox of being better in science than in reaping the economic benefits of the research can only be overcome if this type of collaboration becomes the standard procedure in Europe.

Scope

Current approaches to manufacturing processes often involve unit operations. Nanostructured materials, however, offer the possibility to combine or integrate multi-operational systems into fewer or single steps. In both cases nanomaterials provide new challenges for manufacturing.

Conventional technologies:

- Synthesis.
- Novel gas phase processes, e.g. plasma- or microwave assisted processes.
- Novel wet processes, e.g. sol-gel processes.
- Dispersion and stabilisation.
- *In-situ* functionalisation and formulation.
- Integration in patterned and final system.

Step-out technologies:

- Self-assembly.
- Self-organisation (with long range order).
- *In-situ* generation of nanostructured materials.

To meet market demands, both conventional and step-out technologies will have to have a scalable design for manufacturing.

Research priorities

Synthesis and processing of ultra-pure materials:

- Understanding and manipulating reactions, nucleation, formation of materials.
- Reproducibility, accuracy, reliability at the level of, or better than, today's electronic manufacturing standards.
- Dispersion, modification, functionalisation of nanomaterials on a large scale.

Quantum and hybrid materials:

- Making use of the "innovation toolkit" provided by quantum scale phenomena, e.g. transport, optical, electronic and biocompatible properties.
- Ensuring that the unique properties of quantum materials are maintained from synthesis to the final integrated system.
- Molecular engineering and fabrication of complex hybrid materials.

Reel to reel manufacturing:

- Flexible functional materials.
- Flexible and large area electronics, conformable solar cells.
- Scale-up by transferring patterning techniques from small scale lab processes to reel-to-reel manufacturing technologies.

Embedded devices and systems:

- Sensing + actuating + responsive materials as basic principle.
- Built-in tiny energy supply for sensors.

Scale-up:

- Software tools for optimising cost versus scale-up for performance.
- Scale-up and replication methods.
- Scale-up 2025: smart synthesis + patterning = function by design.
- Inline and online nanometrology tools (linkage to analytics).

Key enablers, linkages and constraints

Moving up the nanomaterials value chain from basic materials synthesis to advanced systems integration is key to a chemical industry renaissance in Europe. The competitiveness of this industry can further be advanced by creating differentiated products that appeal to the emotions and senses of end customers.

Concerning process and material properties design, there is a strong linkage to the reaction and process design pillar of this platform.

Material sciences and manufacturing technologies under SusChem may have also strong links with the ManuFuture ETP as well as the nano manufacturing platform under preparation. The aspects of health, safety and environmental issues of nanomaterials production are addressed by the Horizontal Issues group of SusChem.

Highlights

- The production and the processing of ultra-pure nanomaterials.
- Integration of nanomaterials into continuous production processes and reel-to-reel manufacturing.
- The development and production of large-scale self-assembled materials, systems and devices.
- Health, safety and environmental issues of nanomaterial production.

Nanotechnology will enable the development of processes for the production of nanomaterials with the same inherent chemical process, in the gas, liquid or solid phase (or any combination), which can lead to different products with differing properties.

- Currently manufacturing processes for nanomaterials are relatively crude and dependent on processes not developed for nanomaterials but adapted to produce nanomaterials.
- Key is to take laboratory-based processes and develop generic and/or specific processes that are designed to produce nanomaterials of required characteristics and potentially narrow particle size distribution.
- Exploitation of these novel processes will lead to production of particles of novel and controlled structure.

Bio-based performance and nanocomposite materials

Bio-based performance and nanocomposite materials are (polymeric) materials that are produced by or from plants, microorganisms and/or other bioprocesses, which feature specific functionality based on the micro-/nanostructure of the material, derived from self-organisation. Further bio-based performance and nanocomposite materials are the result of the rational design of biomaterials utilising the principle of self-organisation.

There is more and more interest in the preparation of modified surfaces for bioadhesion, biosensing, and drug delivery. Therefore multidisciplinary research needs to be promoted combining elements of organic and polymer synthesis, physical methods, biotechnology and even engineering. The combination of proteins and inorganic materials, often with specific nanoscale geometries, offers new and innovative product areas such as self-cleaning, self-repairing and sensing products. A variety of thin-film processes and surface investigation techniques can be applied to new synthetic materials and biotechnology oriented projects. The development of new polymers using biotechnology is a field of research of enormous potential. Combinations of naturally occurring polymers and biomaterials, as well as synthetic polymers and biomaterials, display a rich variety of complex structural and dynamic behaviour. Other examples are the design of new multicomponent materials and network polymers with materials such as chitosan derivatives and polyalkylene-glycols.

Scope

The motivation to investigate bio-based materials resides in the potential to reduce the dependency on fossil resources, and the inspiration that can be provided by nature from self-assembly and self-organisation effects. New bio-based performance and nanocomposite materials will be useful in solving a number of problems that European society faces:

- **The high intake of relatively unspecific drugs to cure major diseases**. Drugs are admitted through the gastrointestinal tract or the blood stream but usually have to be effective elsewhere in the body. Specific, biodegradable, non-toxic controlled delivery systems would be ideal to carry the drug to the target and release it there and only there. This would dramatically lower the total amount of drug needed and would enable the use of much more efficient drugs. For similar reasons these systems could be employed for dispensing nutrients (health-improving, disease-preventing compounds) as a preventative measure against illness and diseases in an ageing society.
- **The lack of rapid tests for diseases**. Rapid, reliable sensors for the presence of certain molecules in biological fluids would enable rapid testing at a stage where diseases can still be curable.
- **The lack of methods for rapid wound healing processes and regeneration of damaged tissue.**

- **The lack of rapid tests for biological contamination.** Microbial contamination, or decay of food, may cause serious health threats, especially to the vulnerable groups, and rapid tests to assess food quality and safety would be beneficial.
- **The need for stronger and lighter materials**, for clothing and upholstery textiles, cars, airplanes, etc.
- **The need for coatings for clothing and upholstery textiles**, etc., with specific performances like antiallergenic properties, therapeutic properties, moisture permeability, stain resistance, antifouling properties.
- **The need for coatings for windows, buildings**, etc., with specific performances like stain resistance, antifouling properties and the like.
- **The need for clean drinking water** in areas where there is only seawater or polluted water.

Research priorities

In order to produce materials with the properties to solve the problems described above, extensive research on both basic and applied subjects is needed. Basic research should be devoted to:

- **The basis of molecular assembly in living systems.** The biological cell functions because of self-organisation, but what is the molecular mechanism? For instance, what is the exact nature of the interactions between proteins and membranes? This should lead to molecular understanding at such a level that accurate predictions can be made concerning the manner of self-assembly of biomolecules, and the magnitude of their interactions.
- **The basis of molecular recognition in living systems.** By understanding how receptors function, the design and production of advanced sensors, for the prevention and timely detection of serious diseases, the detection of toxic agents and biohazards at low concentrations, etc., becomes possible.

Key enablers, linkages and constraints

The European biochemical industry and academia are frontrunners in the field of bio-based materials, this despite the considerable gap that exists in R&D investment when compared to the USA and Asian countries. The strong cooperation between respective research groups throughout Europe is one of the key strengths of the biochemical sector.

Highlights

- Bio-based materials created by controlled self-assembly.
- Detectors based on synthetic biological sensors.

Nanotechnology will enable the development of bioelectric and bioorganic/inorganic systems for regenerative medicine.

3 Chemistry for Nanoscience

The Royal Society and The Royal Academy of Engineering[16] define:

Nanoscience as the study of phenomena and the manipulation of materials at the atomic, molecular and macromolecular scales, where properties differ significantly from those at a larger scale.

Nanotechnologies as the design, characterisation, production and application of structures, devices and systems by controlling shape and size at the nanometer scale.

Significant drivers and impulses for material science and technologies originate from the field of chemistry and chemical engineering. To maintain Europe's leading position in the field of innovative materials technologies for the future, it is fundamental to be the very best at chemistry. To achieve this goal, the European Research Council should consider chemistry as a fundamental focus of its research priorities, with long-term research programmes beyond 2025.

As chemistry is an enabling science, research into the fundamentals of nanoscience will give the European research area and consequently the European Union the edge over its global competitors. In the field of nanoscience, the work and research being conducted to date is (still) largely empirical, therefore, there is an great need to develop the fundamental understanding and knowledge associated with working at the nanoscale. Nanoscience provides an understanding of a nanomaterial or particle with its environment. The major challenge facing academics is to be able to predict the change in any (material) property when changing the size scale from above 100 nm to below 20 nm.

At present the contemporary understanding of nanoscience is used to enhance existing materials and products, but in the future it will lead to new interesting products by design. Nanoscience is a disruptive, out-of the box discipline, but nonetheless a key-enabler, leading to innovation, growth and a better quality of life. Industry can and should consider nanoscience and its related nanotechnologies as an **innovation toolkit**, which can lead to new materials at the nanoscale, which spawn new products and ideas for the market and assist in creating up-and-coming markets.

An important facet that needs to be addressed for the successful exploitation of nanoscience is the involvement of the public, governments and stakeholders in an open and transparent discussion. SusChem as the technology platform, the European Union Directorate General for Research and the Chemical Industry need to be active participants in communicating with the whole community.

The potential of nanoscience lies in the ability to provide new applications in the fields of catalysis, higher reactivity in synthesis, better biocompatibility, and enhanced electrical and mechanical properties.

Reaction and process design is of vital importance for the chemical and biochemical industries. Innovation in this area aims to incorporate highly efficient, inherently safe and environmentally benign technologies; tailor-made products with designed properties making efficient use of resources; and increasingly flexible, affordable equipment.

Reaction & Process Design

1 Introduction

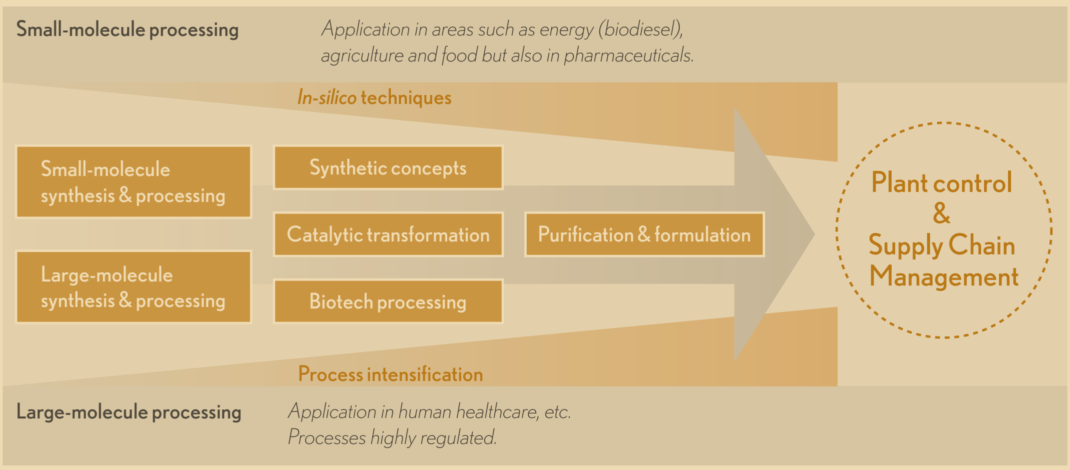
The way one manages the valuable natural resources, designs industrial products and processes, safeguards human health or grows food is undoubtedly influenced by how one uses the material resources. In order to achieve a sustainable development, much progress is needed in the application of science for the identification, design and development of appropriate products and processes that will produce them. Consequently, SusChem has identified reaction and process design as the basic set of key enabling technologies towards sustainable development.

To make progress, there is a need to incorporate the idea that technologies employed for the manufacturing and processing of current and future products such as chemicals, materials, food, drugs, etc., must involve minimum resource utilisation and environmental impact together with optimum "desired" product quality and efficient, cost effective production and marketing. This is the underlying goal of reaction and process design and any effort for effectively harnessing chemical technologies and innovations.

The field of "reaction and process design" represents the fundamental enabling technologies contributing to the entire lifecycle of processes ranging from product development through process development, plant development and operation to product handling and logistics. Integrating the complementary approaches of chemical synthesis and process design and engineering can be applied to all areas of chemistry and biotechnology, thus providing key contributions to all relevant steps from reaction to viability of process plants.

Reaction & process design aims at processes designed from the start to incorporate: highly efficient, inherently safe and environmentally benign technologies; tailor-made products with designed properties making efficient use of (e.g. renewable) resources; smaller size facilities based on process intensification technologies with maximised re-use of materials; equipment that is geared for multiple usage and purpose thus increasing flexibility and decreasing costs; and chemical plants that are equipped with appropriate control systems for the reactions they process. Hence, reaction & process design should be considered as the main driver for sustainable development of the European chemical industry, and fosters innovations, which directly address the needs of the society in terms of, for example, energy, transportation, environmental protection, healthcare and quality of life.

Figure 7.1: Reaction & process design research priorities: contributions to the entire process lifecycle.



The *Reaction & Process Design* section of SusChem identified the following seven research areas, which exert particular impact on the objectives and societal needs mentioned above:

- **Novel synthetic concepts** aim at cost effective new synthetic pathways with a reduced number of steps, higher energy efficiency, lower raw materials consumption and avoidance of by-products and waste. Specific approaches utilising alternative, especially renewable, feedstocks to create a broad slate of different chemicals will start to supplement chemical production starting from classical oil refineries, thereby reducing dependency on oil as the dominant raw material.
- **Catalytic transformations** specifically enable chemical processes to be realised in a cost-, energy-, and eco-efficient way. Catalysis provides key contributions to sustainable mobility, clean fuels production, the rational use of resources including alternative raw materials, sustainable energy (fuel cells, use of solar energy) and environmental protection (air and waste water purification, solid waste reuse, reduction of greenhouse gas emissions, soil and water remediation).
- **Biotechnological processing** aims at e.g. the combination of genetic engineering methods and analytical high throughput processes to considerably speed up biocatalyst and process development, thereby enabling economically competitive bioprocesses with the potential to complement or even replace chemical processes and also to pave the way for new products.
- **Process intensification** aims at the reduction of process steps as well as use of novel and more eco-efficient synthesis routes enabling greater production with smaller/cheaper equipment, less energy consumption, smaller quantities (or even absence of) solvents, substantially lower risk, reduced environmental impact and higher selectivity for similar or even higher conversions of reactants.
- ***In-silico* techniques**, driven by accelerating developments in high performance computing, chemical sensing technology and distributed process control, result in design of new catalytic and/or multifunctional materials, enhance operational efficiency of industrial processes and enable development of flexible processes suited for the production of a wide range of products in a single unit.

- **Purification & formulation** processes support zero-emission plants producing purer products conditioned to suit market needs. They strongly alleviate the impact of the chemical industry and products on the environment and human health. Innovative technologies will enable cheap purification of substantial product streams thereby reducing energy and material consumption by 25% and achieve zero-waste production for at least 20% of existing technologies.
- **Plant control & supply chain management** aim at a production and business paradigm shift towards knowledge-based, model-centric manufacturing, subsequently strongly increasing efficiency and flexibility of the European chemical industry. Advanced plant control, process performance monitoring and supply chain management result in flexible, inherently safe production plants with optimal market demand responsiveness.

Vision

- Production plants with increased productivity and efficiency, and reduced cost of manufacturing.
- Flexible production plants equipped with appropriate process control systems and equipment that is geared for variable scale and scope.
- Production facilities having minimal environmental impact and utilising more benign materials, while maximising recycling.
- More inherently safe design of production facilities leading to near zero accidents in chemical manufacturing.

2 Research Areas

Synthetic concepts

Scope

Devising novel synthetic concepts is a continuous research task in chemistry. The major challenge in this field is the need to step out of the conventional framework of thinking, both with respect to reagents and with respect to process conditions in order to achieve breakthrough improvements. Novel synthetic concepts cover the whole range of chemistry, including novel transformations, application and production of alternative feedstocks, new reaction media and reaction conditions, and/or innovative cheaper, shorter or more benign pathways to known products. Synthetic concepts, however, can never be considered isolated, but have to be developed in parallel with equally advanced reaction engineering concepts. Novel synthetic concepts could therefore benefit, especially from advances in catalysis and process intensification.

Research priorities

In particular, research in the following directions is important in order meet the economic and ecological challenges which chemistry faces in Europe up to 2025:

- Substitution of organic **solvents** by replacement with water, supercritical fluids, ionic liquids, or the development of solvent-free processes.
- Use of **novel building blocks** for synthesis, such as CO_2. Short-term targets are syntheses replacing phosgene, in the long run, broad application of CO_2 as a C_1 building block or direct dinitrogen activation should be targeted.
- Introduction of **novel feedstocks** based on biomass, utilising pre-formed fragments of target molecules to exploit pathways with reduced number of steps. Short-term targets would be syntheses starting from glycerol (as a by-product of biodiesel production), in the long run, a broad range of different biomass derived feedstocks will be used for chemical production.
- **Reducing the dependence on oil** by conversion to gas and/or coal as raw materials for chemicals. Short-term targets are direct oxyfunctionalisation processes for methane, longer-term research should focus on energy efficient and clean technologies for making use of gas and coal in chemical production.
- Improving efficiency by **smart synthesis design** and reduction of the number of reaction steps. Short-term targets are the improvement of fine chemistry synthetic routes, for instance by introducing catalytic steps instead of stoichiometric ones or by using integrated multicomponent chemical processes, in which a sequence of synthetic steps is converted into a one-pot multicomponent process where three or more reactions take place in a perfectly controlled and ordered way. On a longer time scale, large scale processes should also be reconsidered and possibly redesigned.
- Develop generic stereoselective methods for the introduction of **chiral centres** in an effective way. Hydrogenations are already well developed; short-term research should focus on increased substrate ranges. On a longer time scale, practical stereoselective oxidations or C-C coupling reactions are highly desirable.
- Increased use of benign and **easy-to-handle oxidants**, such as hydrogen peroxide or molecular oxygen. The short-term focus should probably be placed on hydrogen peroxide, in the long run, oxygen seems to be the desirable oxidant.

- Using **innovative means for energy input**, such as plasma technology, microwaves or light, which may also allow novel reactions. On a short time scale, the fundamental effects of using such methods need to be studies, long-term goals are the introduction of these methods into commercial practice, where useful.
- Development of experimental and theoretical concepts to adapt efficiently synthetic methodologies to **new substrates**. High throughput experimentation as means for the strongly accelerated adaptation of processes to new substrates is the short-term objective, while theoretical concepts to allow the expansion of the substrate range will become available on a longer time scale.
- **Elimination of protection group strategies**. The necessity to protect and deprotect functional groups adds to the number of steps necessary to reach a synthetic target. It reduces yields and leads to increased waste production. More selective transformations, which only affect the desired functional groups are urgently needed.
- Development of **short contact time processes** which have higher space-time yields and will be adapted to more intense processes. This could also allow the conversion of batch processing to continuous processes in small-scale devices. Initially, suitable chemistries have to be developed, while process implementation is the long-term goal.

Novel synthetic concepts also include the conversion of production processes based on classical chemical transformations to biotechnological pathways where these are more efficient. Such approaches are covered in more detail in a different section of this chapter.

Key enablers, linkages and constraints

The goals formulated above require cooperation across the subdisciplines of chemistry and between industry and academia. An important step has already been reached in the formulation of a research agenda which is common for all stakeholders. The manner in which each of the tasks will be tackled will vary. However, it is clear that substantial progress can only be reached if the tasks are broken down into manageable work-packages which can also be addressed by small, powerful teams instead of by large networks. In these teams, industry and academia should be equally represented, and exchange of staff between the two sectors would be highly desirable.

Interaction between academia and industry needs to be further strengthened, so that close feedback between the needs of industry and innovative concepts developed in academia is provided. Difficulties in the introduction and development of new concepts will be encountered if the conditions for chemical production in Europe become more unfavourable, since high research intensity will only be maintained in world regions, where there is also a strong chemical production.

Highlights

- Tap biomass, gas and coal as feedstocks for a wide range of products thereby reducing dependency on oil.
- Substitute organic solvents and develop solvent-free synthetic concepts.

Catalytic transformations

Scope

More than 80% of the processes in the chemical industry (including pharmaceuticals), worth approximately €1,500 billion, depend on catalytic technologies. Next generation catalysts should contribute to achieving zero-waste emissions and selectively use the energy in chemical reactions. They also will enable the development of new biomimicking catalytic transformations, new clean energy sources and chemical storage methods, utilisation of new and/or renewable raw materials and reuse of waste, solving global issues (greenhouse gas emissions, water and air quality) and realising smart catalytic devices for health protection and the improvement of the quality of life, such as "self-cleaning" ovens or tiles that are self-cleaning or prevent algae growths.

The solution of these challenges for the future requires the development of the common scientific bases which allows a change in the approach from the search of individual solution to the design and synthesis of tailor-made catalysts, and the development of a true technological platform to be used by several industries.

Research priorities

Shorter term research on catalytic transformation should provide new catalytic materials and reactions, by optimising the integration between expertise-, knowledge- and fast screening-oriented methods. On a longer term vision a non-evolutionary change is necessary with a holistic integration of the different areas of catalysis and by putting knowledge-based catalyst design at the heart of development. New research in catalytic transformations should address the following long-term (10-20 years) priorities:

- **Towards 100% selectivity and zero-emission processes**. Design of the next-generation of multifunctional catalysts, by integrating knowledge on hetero-, homo-, single-site and biocatalysts, to achieve 100% selectivity in multi-step and complex syntheses, and avoiding waste formation.
- **Use of non-conventional energy sources**. Exploring new reaction pathways requires a new effort in developing catalysts to be used with non-conventional energy sources (light, electrons, microwave and ultrasound).
- **Use of alternative and/or renewable raw materials**. There is the need for new catalysts for the selective functionalisation of alkanes, gas-to-liquid conversion, use of biomass and waste for energy and chemical applications.

- **Catalysis for environment**. New catalysts and catalytic technologies should be directed at reducing greenhouse gas emissions (CO_2 conversion to chemicals and fuels, for example), circumventing the breakdown of the ozone-layer, and solving water and air issues. Catalysts will also find increasing use in soil and water remediation technologies.
- **Clean energy and mobility**. Clean fuel production, meeting the challenge of a widespread use of H_2, development of efficient methods for chemical energy storage, minimisation of the impact on the environment of mobility, require the development of new and/or more efficient catalytic solutions.
- **Improving health and quality of life**. New catalysts and catalytic concepts are necessary to address issues such as indoor and outdoor air quality, purification of drinking water, self-cleaning materials, and catalytic smart sensors.

These long-term objectives require meeting a series of shorter-term (5-10 years) objectives:

- **Towards tailor-made production of nanoscale materials**. There is the need to develop new methods of synthesis for better, tailor-made control of nanosized catalytic objects and their assembly into a 2D or 3D architecture.
- **Integrate reactor-catalyst-separation design**. Integration and intensification of processes requires the development of new catalytic concepts which break down the current barriers (for example, low flux in catalytic membranes).
- **Develop nanoscale reactors**. Functionalised carbon and metal-oxide nanotubes, new tunable membranes, novel micro- and mesoporous materials, organic-inorganic hybrids offer breakthrough possibilities to develop nanoscale reactors in which confinement effects may induce radically new reactivities. Enzyme and microorganisms may be modified to produce or assemble nanoscale catalysts and reactors.

- **Explore unconventional reaction conditions**. It is necessary to intensify the research in unconventional reaction conditions (temperature, pressure, space-velocities), using new clean solvents (ionic liquids, supercritical and CO_2-expanded solvents), catalysis with radical and high-energy species (catalysts with non-thermal plasma or radiation, for example), and operations under unsteady state conditions.
- **Biomimicking catalysts**. Integration of knowledge between single-site, homo-, hetero- and biocatalysis allows for the design of new robust biomimicking catalysts to substitute or integrate with enzymatic and microorganisms driven processes in order to widen their use, reduce sensitivity and increase productivity. New synthesis processes for chiral molecules can be developed with these catalysts.
- **Improved methods of understanding of the working catalysts**. Characterisation of the structure/surface of the active sites during catalytic reaction at the molecular and nanoscale level, understanding the dynamics of transformation, and determination of the nature, mobility and rate of transformation of surface adspecies are some of the challenging problems, the solving of which will be the basis for the design of next generation of catalysts.

Key enablers, linkages and constraints

To turn vision into reality requires a progressive change from search to design in catalytic transformation, discovery and development. The design and implementation for showcase applications must be done in a concerted action between academy and industry. Applications should indicate the direction of research, but the driving force should become the development of new concepts for synthesising catalytic materials, understanding the mechanisms of catalytic transformations and tailoring the assembly of catalytic sites or multi-functionalities in a single site. This change will provide a coherent framework for progress and innovation in catalytic transformations..

Highlights

- Development of catalysts to shift from an oil- to gas-based chemistry and to use biomass, or even waste, as a source of fuels and chemical products.
- Boosting catalysis to a new level of operation at 100% selectivity in complex, multistep reactions.

Biotechnological processing

Scope

In the past few years conditions for the application of biotechnological processes in industrial production have improved. New tools, such as screening methods and metabolic engineering, and also global analysis methods, such as genomics, proteomics, metabolomics, and bioinformatics tools, are gradually becoming more widely available. These new instruments make it possible to reduce the time needed to develop and establish new industrial biotechnological products and processes; to develop biocatalysts (enzymes) and microorganisms which render manufacturing processes more economical and facilitate new manufacturing processes and, for the first time since the beginning of the oil age in the early fifties, to apply processes with economic potential in the production of basic chemicals and biopolymers. It is time to intensify, extend and implement this new potential of biotechnological methods in industry so that it can hold its own both independently and in synergy with chemical processes. From the very outset biotechnology should be included in decision making as an alternative to chemical processes. It has the potential to replace several chemical process steps by one enzymatic or fermentative production step that is both cost-effective and environmentally benign.

This chapter on biotechnological processing focuses on process technology aspects of industrial biotechnology. It is complementary to Chapter 5 *Industrial Biotechnology* and in several cases describes research priorities, which are also mentioned there. It is the aim of this chapter to emphasize, that the approaches of chemical reaction & process design and biotechnological reaction & process design comprise many parallel elements and synergies. Both approaches will increasingly supplement each other and become intertwined technologies. Further differentiation between biotechnological processing and industrial biotechnology will be subject to the implementation action plan.

Research priorities

- **Biocatalyst improvement by strain optimisation.** Biotechnological process development must be founded on a broader genomic basis, tapping into the huge number of unknown biocatalysts based on the millions of naturally occurring microorganisms as opposed to the only 100 microorganism strains currently used in approximately 130 industrial processes.

- **New technologies as the basis for novel optimised biocatalysts**. Exploitation of new emerging techniques for quantitative metabolome analysis (metabolic fingerprinting, metabolic profiling), supplemented by technological developments such as pre-calculation of 3D enzyme-structures, development of protein-protein interaction cards based on measurement techniques, and in vivo imaging techniques with reporter molecules to determine complex effects quantitatively and holistically. There is every reason to expect that systems biology is a good basis for new process strategies.

- **More rapid development and industrial application of biocatalysts – shorter time-to-market**. In addition to high throughput screening and selection processes apply thermodynamic principles to the assessment of biotechnological processes (metabolism modelling, downstream processing). This goes hand-in-hand with the need for a high degree of miniaturisation and parallelisation of plant engineering in the framework of micro bioprocess engineering. This explicitly includes downstream processing, which is frequently the main cost factor, although in typical process developments it is often neglected. It is imperative to develop novel downstream processes for low- and high-molecular products and to promote techniques which facilitate the effective identification of suitable purification strategies approaches, e.g., by improved mechanistic understanding.

- **Biocatalyst optimisation by protein design**. Rapid, tailored development of new enzymatic processes by applying current techniques of directed evolution and genome shuffling, particularly in connection with high throughput processes for massively parallel analysis of different biocatalysts. The result of such selection and screening processes is optimised enzymes which can either be used in isolation or in a whole-cell approach as biocatalysts.

- **Bioprocess control and intensification**. Optimum control of industrial biotechnological production processes using biosensors as online signallers for optimum control using novel approaches, such as transcriptional or cell morphological signals. Likewise, the development of new process and reactor models should be intensified so that the full potential of process control and plant design can be ascertained.

- **Enable competitive biotechnological processes and facilitate the production of new products**. The availability of adequate raw materials (especially with the use of renewable resources) for biotechnological processes has to be guaranteed and capacities for recycling residues from biotechnological processes have to be clarified. This includes avoiding undesired by-products or by-products that cannot be recycled economically.

- **Chemical engineering development on advanced separation methods for bioproducts**. Enhancement of bioprocesses efficiency developing novel technologies supporting product collection during the fermentation process, going towards semi-batch and continuous production methods, where total process efficiency and product selectivity can be controlled and improved.

- **Combine synthetic chemistry methods with bioproduct recovery to shorten the reaction times**, and improve yield of the desired product. Bioproduced molecules are seen in this context as platforms for product families of functional and value added end products.

Key enablers, linkages and constraints

The chemical industry itself developed many of the classical chemical methods it applies today. In the case of biotechnological methods this is rarely the case due to the high development costs, the largely non-existent (but necessary) expertise in the company and the hitherto lengthy development period, at least in SMEs. Here it is often young start-ups that develop technologies, patent them and even offer them to the chemical industry to use in the framework of various different business models (services, licensing, development partnerships, etc.). Many young firms and start-ups have adopted the role once held by the central research departments of large-scale chemical companies; this makes for a meaningful development from an economic viewpoint as it is a means of sharing the burden of high development costs among several companies or several products.

Highlights

- Building of biotechnological production networks in biorefineries, to divert by-products to parallel processes and thus to work more economically.

Process intensification

Scope

Intensified process equipment and production systems as well as process integration are key enabling factors for a step-change improvement in process/plant efficiency, with respect to space, time, energy, raw materials, safety and the environment. New research must cover a much broader range of production scales and production applications and development must move from individual devices to complete integrated production systems. Widespread application of intensified and/or integrated production requires devices operating under a broad range of conditions, and the developments of such devices should be accompanied by a movement toward truly novel synthesis routes for more effective chemicals production. Research should address issues in scale-down for "ultra" small-scale production of extremely high value-added products early on in the development stages (pharmaceuticals for clinical trials, etc.), scale-up for "precision engineering" of a product's end-use properties (such as droplet and grain-size distributions, crystalline polymorphism, isomeric ratios, etc.) for high-tonnage sectors (including polymers, consumer goods, etc.) through locally targeted process control (integrated sensors and actuators), as well as heat-mass integration (combine identical equipments operating as sources and sinks of utilities). Research should extend also to the impact of new production methods (distributed production, etc.) on safety, plant organisation, supply-chain logistics and market response.

Research priorities

Mid-term:

- **Improving quality and reliability of intensified components and devices**. In particular, research should focus on low-cost fabrication and connection technologies, robust materials, resistance to corrosion and clogging, superior performance with regard to maintenance and reliability for applications under highly demanding conditions of temperature and pressure in aggressive and/or unusual media (supercritical fluids, ionic liquids, high temperatures, solvent-free reaction media, etc.).
- **Developing local process control and energy supply**. Priorities involve integrating robust miniaturised sensors and actuators for locally targeted process control, as well as enlarging the scope of process intensification through targeted energy supply for precise control of chemical transformations and reaction pathways, including use of novel energy sources (e. g. electrochemical, photochemical and microwave devices).
- **Extending processing options for continuous operation**. A major challenge is the invention of methods for continuous processing of highly viscous and/or process fluids containing solids in intensified devices, as well as the development of dedicated, small, continuous processes at reduced cost. A major objective should be a substantial drop in capital expenditure for new plant and/or for retrofit of high-performance intensified devices into existing infrastructure (due, for example, to operation in much smaller equipment volumes).
- **Process intensification** through integration of heat/mass, reaction/separation, etc.
- **Creating reliable risk and benefit assessment methods**. Among the major issues to be addressed is the creation of new business models for effective, sustainable industrial exploitation of intensified production, as well as criteria for evaluation of safety, reliability and operability of intensified plant.
- **Adapting design procedures and operational and supply chain management**. Priority should be given to flexible layout and targeted control for integration of intensified components in plant, as well devising specific virtual prototyping for novel and/or unusual process devices.

- **Identifying the design targets for achieving minimum utility demand**. Priority should be given to flexible layout and targeted control of integration of components in plants without sacrificing process operability.

Long-term:

- **Adapting intensified process equipment to advances in nanotechnology**. Research should be multidisciplinary and involve integration into intensified process equipment of nanostructured materials and specifically tailored chemical and biochemical catalysts, enzymatic synthesis, immobilised cell cultures, etc.
- **Implementing self-adapting process devices**. Research in this area should target a new generation of extremely flexible, high-performance process equipment, developed through integration of self-adapting materials (shape-change alloys to create "intelligent" valves, piézo-electric components, etc.).
- **Creating intensified product engineering**. The objective should be to apply process intensification to specifically targeted production of end-use properties, including accelerated scale-up methods from bench-top to production scale. The long-term goal should be to combine knowledge of structure-property relations to define necessary conditions for precise locally targeted process control in formulation engineering for rapid response to consumer demand, changing market requirements and mass customisation.

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Key enablers, linkages and constraints

Enablers:

- Developments in materials technology and microfabrication methods.
- Improved process modelling and computer-aided design.
- Advances in microfluidics and related disciplines.
- Concurrent process-product engineering.

Links:

- New materials: links both for the development of new materials for the process devices themselves and for the use of intensified processing to produce new products and materials.
- Industrial biotechnology: links to enzymatic and biochemical catalysis, as well as to process intensification of process involving immobilised cell cultures, genetically modified organisms, etc.

Constraints:

- Traditional economies of scale (favouring low-intensity, high-volume operation). For widespread use of intensified process equipment, including the possibility in some cases of distributed and/or delocalised production, a true reduction in required capital investment is a clear constraint for industrial competitiveness.
- Requirement of a new generation of equipment manufacturers capable of producing the required devices and components at low cost. Standardisation is also an issue for interconnection and retrofit.

Highlights

- Create truly "programmable" chemical reactors whose local operating conditions adapt automatically to changes in feed composition, product specifications, etc.
- Enable new, competitive business models based on distributed, on site and on demand production on the basis of intensified, integrated process equipment.

In-silico techniques

Scope

The recent and accelerating developments in high performance computing (HPC), process systems engineering (PSE), chemical sensing technology and distributed process control will ensure that *in-silico* techniques will have a revolutionary impact on the way the chemical industries operate in the next 20 years.

The ultimate objective of *in-silico* techniques is the integration of theoretical chemistry, physical chemistry and hydrodynamics at the molecular scale through to the operation of a catalyst at full scale under steady and unsteady state operation. The range of time and length scales that need to be considered is vast, but the integration of currently existing and yet to be developed modelling methodologies will lead to powerful tools allowing definition of an active site, the quantification of the surface chemistry, determination of the rate determining step through to a rationally based rate equation. *In-silico* techniques will play an ever-increasing role in all aspects of the chemical industries with the growing requirements of data storage, retrieval, harvesting and mining. With data coming from every step in industrial processes the area of informatics will become an ever more critical area. Only through the linking of all scales of modelling one can achieve the optimum process and plant configurations. In order to articulate these ultimate goals it is sensible to divide the area into appropriate steps.

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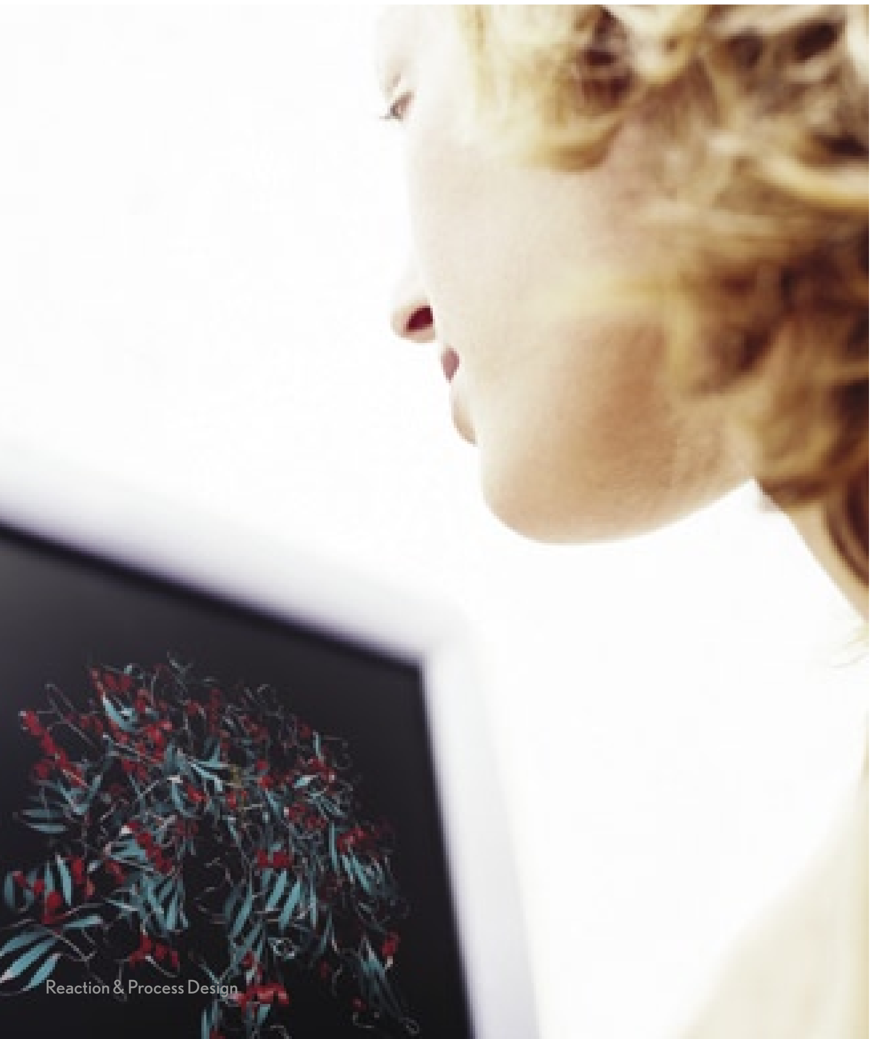
Research priorities

- **The theoretical modelling of complex homogeneous and heterogeneous systems** will have to be significantly developed. The models will have to become much more sophisticated and include such things as solvation effects and transition state calculations, etc. This will need significant code and HPC hardware implementation as well as the appropriate protocols for parallel calculations.
- Chemical reactions will have to be studied in a much more rigorous way than today to establish accurately **the reaction cycles and kinetic models**.
- **Data mining, optimum selection and integrative analytics** will have to be developed for real-time operation research and modelling and simulation fundamentals.
- Further development and validation of **models for the complex multiphase systems** often encountered in industry, e.g. slurries, bubbly flows, including interphase mass transfer, particle agglomeration and attrition, bubble break-up and coalescence, reaction etc. This too may require the development of new experimental techniques.
- **Process systems engineering (PSE) techniques** will be used for designing processes and products together to ensure that products with real potential for manufacture are taken forward.

Particular emphasis should be placed on the following application areas:

- Integrated process simulation utilising cheminformatics for catalysis, and from process development, scale-up to full plant operation.
- Pharmacokinetic simulation (ADME) at a quality, approaching the level of *in-vivo* experiments.
- Biokinetic modelling of chemical plants used in the design of ideal and non-ideal bioreactors.
- Catalyst design, providing theoretical direction and subsequently routine predictive design of catalysts.
- Mechanisms and kinetic models for accurate theoretical description of homogeneous and heterogeneous catalysed reactions and close coupling of theoretical and experimental investigations.



Key enablers, linkages and constraints

By their very nature, *in-silico* techniques are intrinsically multidisciplinary and involve multiple length and time scales as well as considering many types of materials and molecules that are traditionally studied in separate subdisciplines. This means that fundamental methods that were developed in separate contexts need to be combined and new ones invented. This is the key reason why an alliance of skills from computational chemistry to applied mathematics and computer science will be necessary for the success of theory, modelling and simulation. A new investment in theory, modelling and simulation should facilitate the formation of such alliances and teams of theorists, computational scientists, applied mathematicians and computer scientists. Generally, experimentalists have to work in much closer collaboration with theoreticians and develop and use characterisation techniques as close as possible to times of reaction transitions.

Highlights

- *In-silico* prediction of pharmacokinetic properties to rationally assess ADME (absorption, distribution, metabolism, and excretion) behaviour in a very early stage of drug discovery.
- Provide a theoretical direction to the synthesis of new catalysts and subsequently achieve their routine predictive design.

Purification and formulation engineering

Scope

In the final steps of chemical product manufacturing the removal of undesired constituents/features (purification) and/or the inclusion of additional required constituents/features (formulation) represent critical steps in meeting customer requirements (e.g. product performance, cost, safety). Societal drivers, such as new legislation regarding product safety and environmental impact require breakthroughs in this field of technology to remain competitive on a global basis.

Tailoring the end-use properties of materials by purification and formulation engineering has a broad scope. Separation technology in a broad sense is dominant in the purification segment. However chemical post-treatment steps (e.g. reactive extrusion of polymers) can be within the scope as well. Improved separation methods with higher selectivities/yields and, especially, less investment and energy effort are key areas for future R&D. Also novel separation methods for complex molecules (biotechnological, pharmaceutical and food applications) are needed.

Formulation engineering also covers a broad field of technologies and applications. For example in the design of disperse particulate products, there is a clear trend for particle dimensions to decrease to submicron/nanoscale, and this will impact new product formulations, where surface design is a key factor. Many different fields of application are covered, for example, healthcare products, food and consumer products. Also in the field of polymer composites, where nanomaterials need to be dispersed in a homogeneous manner, advances in formulation technology are critical in the development of innovative products.

Research priorities

Mid-term:

- **Separations with alternative sources of fuels and raw materials**, e.g. biomass, fuel cells, clean coal technologies.
- **Integrated separations**, e.g. reactive separations, divided wall columns, hybrid processes, etc.
- **Formulation of designed products with defined particulate structure**, e.g. micro/nanostructured emulsions and dispersions, dust free, free flow, hydrophilic/hydrophobic, controlled release, redispersability, etc.
- **Efficient computer aided modelling of purification and formulation processes and their sequences**, e.g. automated process synthesis, predictive multiscale process models with accessible databanks on model parameters.

Long-term:

- **Developing the base sciences** e.g. in affinity, molecular recognition, membranes, but also ongoing fundamental research on crystallisation, chromatography, extraction, adsorption and distillation.
- **New CO_2 capture and separation technologies**.
- **Purification and formulation methods for technology to enable the increased use of biomaterials and bioprocesses.**
- **Development of perfect mixing**; e.g. enabling the manufacture of new polymer composites.
- **High purity products by innovative purification/formulation**; e.g. new medicines and electronic materials, bioproducts from aqueous solutions.
- **Ongoing effort on the development of more environmentally benign technology**; e.g. lighter and stronger materials, water purification technology.

Key enablers, linkages and constraints

Enablers:

- Need for more environmentally friendly products/ technologies (future legislation, incl. food safety).
- Coping with higher cost/lower availability of energy and raw materials.
- Increased availability of new materials (e.g. ion exchangers, (affinity)-membranes, solvents).
- More demanding customer requirements on product functionality/cost/safety.
- Increased collaborative initiatives between industry and academia.

Links:

To *Materials Technology* and *Industrial Biotechnology* sections, as well as to all other research headings in the *Reaction & Process Design* section. Other links to national initiatives, e.g. Dutch Technology Roadmap on Separation Technology ("Let's Separate Together", Sept. 17, 2004).

Constraints:

The European public/government underestimates the importance of the chemical industry, resulting in insufficient or investment which is too late in public research (e.g. FP6) in this cross-cutting field of technology. Industrial production of chemicals and R&D may move out of Europe.

Highlights

- Improve mature technologies and implement emerging separation methods (e.g. membranes, plasma treatment, electro-magnetic , ultra sonic applications) with lower energy intensity, legislative compliance and improved quality/functionality as mature technologies.
- Design of sub-micron/nanoscale disperse particulate products with tailored surface and structure properties.

Plant control and supply chain management

Scope

Chemical process industries provide invaluable base materials for virtually all economic sectors, from food & health to automotive. These industries are sometimes considered to be part of the "old economy", traditional, manufacturing products with limited flexibility to adapt to changes in demand. Many of the challenges for industries stem from a lack of understanding and predictability of plant component performance and production processes. This leads to production and market behaviour with limited flexibility, causing suboptimisation in value chain perspective.

The current state-of-the-art still does not permit wide use of real-time, high-quality model based predictions in process industries, as models are too costly and too complex. Research has to deliver advanced modelling methodologies not only for complex continuous flow and batch processes but also with respect to lifecycle issues. This modelling will enable a step change in process design, operation, maintenance and supply chain management tools, that support a new knowledge based production paradigm and business model for chemical process industries, enabling them to deal proactively with rapidly changing market demands.

Novel research approaches need to focus on a breakthrough to generic, low cost, fast, first principle-based modelling methodology for complex continuous flow and batch processes as well as for lifecycle management. In conjunction with significant research efforts in plant analyser and process control technology, as well as novel approaches in plant design and operation, this innovation will deliver next generation tools for the demanding tasks of:

- Computer aided process and systems engineering for flexible and intensified processes.
- Advanced process performance monitoring based on intelligent model based soft sensors and advanced analytical instruments (RMA, NIR).

- High performance non-linear process control.
- Integrated supply chain management bridging the gap between supply chain network planning, detail scheduling and process design and operations.

Research priorities

Meeting the challenges in plant control and flexible manufacturing requires a step change in integrated process and plant operation modelling supported by research in process control systems and process analyser technology as well as innovative approaches in plant layout. Further to the modelling aspect, the field of supply chain management in chemical industry calls for significant research work for the development of new methodologies to fully exploit the potential for improvements in efficiency and service quality. The following list contains major research priorities for the respective areas:

Innovation in process modelling

- Systematic methods and tools for easy and very rapid development of maintainable consistent lifecycle process models for process and equipment.
- Development and integration of new materials solutions into advanced lifecycle concepts.
- Application-oriented model reduction technologies for the generation of reduced models for real-time optimal plant-wide process operation and predictive control.
- Model-based process monitoring for efficient, reliable and cost effective process performance monitoring and systems maintenance.
- Closed loop dynamic real-time optimisation even for large-scale plants (with multiple production processes).
- In-line asset management determining forecasts for the equipment conditions and effectiveness.
- Supply chain compliant dynamic scheduling.

Process analyser technology

- From on-line to in-line analyser technology.
- Development of advanced process analysers:
  - Immunoassay analyser for healthcare applications.
  - Tomographic analyser technology.
  - Innovative magnetic process analyser (e.g. SQUIDS).
- Miniaturisation of process analyser for micro-technology applications.
- Development of new monitoring tools for continuous assessment of plant component state and residual life time.

Supply chain management

- Collaborative planning and control of transport and stock keeping.
- Revenue management.
- Inventories planning under uncertainties.
- Advanced network design for production and distribution systems.
- Reverse logistics strategies and operational control for the logistics of swaps.

Key enablers, linkages and constraints

Enabler:
Dynamic development of computational power, development of new sensor principles and innovation in mathematical optimisation routines.

Linkages:
In the true spirit of supply chain management, particular emphasis has to be placed on collaborative initiatives involving producers, their customers and logistics service providers.

Constraints:
Some of the described innovation challenges will require fundamental changes in business processes, trading practices and managerial mindsets.

Highlights

- Enable real-time process control using intelligent sensors and inline-process analysers.
- Supply chain management (collaborative planning and inventory planning) aimed at transportation.

A strategic approach to innovation should focus on value creation rather than only cost reduction or environmental performance. SusChem's Horizontal Issues group effectively addresses the integration of all the factors underpinning sustainable innovation, from regulatory to economic, environmental and societal.

Horizontal Issues

1 Introduction

Industry led Technology Platforms serve the broad interests of EU citizens by providing technological solutions for the innovations needed by society. The successful introduction of a new technology is often dependent on an effective public dialogue on its costs, risks and benefits. However, with so much media focus on sensationalism, this increasing public awareness often leads to an excessive focus on potential negative impacts. This is a particularly acute issue for chemistry-related technologies as their benefits have not been effectively communicated with society. This can be accentuated by the failure of those without a specialised technical background to communicate effectively with those members for society (stakeholders and the general public) with a less developed understanding of the issue. Finally, in common with many high-tech areas, the successful introduction of new chemistry-related technologies is also, in large part, dependent on adequate financial resources and on the supply of appropriately trained people.

The goal of the Horizontal Issues Group (HIG) is to address the concerns of key stakeholders and to ensure that the EU becomes the favoured location for innovation within chemistry* and industrial biotechnology.This will be achieved by creating a positive environment for chemistry and by identifying those factors that could hinder or enhance the success of SusChem.

The Horizontal Issues Group provides a support function for the overall SusChem vision. In particular the HIG will deliver action programmes that contribute to the earlier and broader societal appreciation of new SusChem technologies, which in turn will foster an increasingly supportive environment for further chemistry-based technological innovations in Europe.

The outputs from the technology areas of the platform and their impact in terms of both potential benefit and risk to different stakeholder groups, as well as HIG's ability to impact the outcome, will determine the priorities for the work that will be pursued.

Each of the three technology sections within SusChem has a specific focus as to how their technologies will address issues of major societal importance. These are addressed in "Societal Drivers" in the *People, Planet, Profit* section. The issues themselves are well known to the public, but what is less well known is how advances in chemistry will contribute to their solution.

Chemistry pervades nearly every aspect of manufacturing within the EU, but its overall role is poorly understood for a number of reasons including:

- The benefits of chemistry to essential products are hidden and often inadequately communicated, whereas the risks and potential negative consequences receive frequent media and political attention.
- There is some mistrust of the industry and, for many European countries, a distrust of any new technologies that the public find difficult to understand.

These issues need to be addressed in order for SusChem to become a real success story.

* For the purpose of this *Horizontal Issues* chapter reference to the word chemistry includes industrial biotechnology, plastics & synthetic materials and indeed all the products and services covered by SusChem.

2 Scope and Goals

Scientific and technological excellence play a critical role in innovation, but successful exploitation of innovation also depends on other factors, including:

- Aligning the priorities for technology work with the more important market needs, including those relating to consumer acceptance of specific applications in terms of products.
- Increasing access to funding and capital, both public and private.
- Adequately addressing societal concerns, and preferences for technology development, in a timely manner.
- Maintaining an appropriate and effective regulatory balance throughout the process.

SusChem activities will mainly take place within a regulatory framework that is already governed by the REACH legislation, however, by their very nature new technologies may require new approaches to stakeholder involvement in order for them to be introduced successfully.

The Horizontal Issues work will include both projects and policy work. By definition the SRA focuses primarily on projects, so the bulk of the horizontal policy work will be integrated into the Implementation Action Plan that will follow on from the SRA.

The level of interactions from the HIG will range from project proposals and possibly management, to setting up virtual networks and stakeholder dialogue. It will also pursue less resource-intensive actions such as providing brief position statements on specific issues. Resource priorities will be allocated according to how effectively they can contribute to creating a more supportive environment for our new technologies and make a substantive impact to our stated goals.

Both the pace and global capabilities for technological progress are increasing rapidly. This requires not only that the SusChem technology areas focus on priorities offering global competitive advantage to the EU, but also that the HIG proactively addresses societal concerns and other barriers that might delay beneficial technological progress. Past experience has shown that when delays are based on unfounded concerns then the development of those new technologies simply shifts to other regions in the world.

To achieve its goals, SusChem must build early confidence in new technologies and secure financial support for their development. Industry should play a role in financing research, but engagement in EU funding programmes and venture capital initiatives must be sought.

The HIG's top-level goal is to ensure that the citizens of the EU benefit from the development and use of innovations based on the SusChem SRA. In particular there is a need to ensure that SusChem technologies lead to wealth and job creation for those citizens within the EU.

3 Projects and Research Priorities

Priority areas for further work within the horizontal arena fit into two themes:

- **Addressing societal concerns** associated with new products and processes. This will involve identification and prioritisation of health, safety, environmental and ethical concerns, and effective strategies to disseminate information on risks and benefits as well as risk management strategies.
- **Support for innovation** which involves the evaluation and enhancement of funding models for innovation and processes to develop appropriate skills sets and improve the human capacity for innovation. In addition different funding options for research and innovation throughout the supply chain will be evaluated, taking due account of the needs of the chemistry-based industries including SMEs.

Societal concerns

Within the theme of health, safety and environment (HSE), there are two issues that are consistently raised by stakeholders. The first involves societal involvement in the introduction of new technologies and the second relates to the development of globally acceptable risk assessment and management strategies.

Promoting public dialogue on SusChem technologies

Enhancing the public's appreciation of new and emerging (SusChem) technologies is a multidimensional process that involves:

Providing stakeholders with balanced information for decision-making

Political dialogue and the resulting media attention often focus on the negative aspects of the debate. In reality all decisions whether to change or not, involve significant trade-offs. All the technology areas address potential trade-offs from the technical perspective, but all potential solutions may also raise significant societal concerns which may drive political outcomes and, in some cases, consumer acceptance of specific consumer products.

Using the breadth of the stakeholder network, the HIG will contribute to developing the optimal socio-political balance between the benefits of emerging technologies and the level of acceptable risk to society, taking into account societal concerns regarding risks, as well as societal perspectives on desirable benefits which will result from application of innovative new technologies.

Lifecycle thinking

A more effective integration of Lifecycle Thinking (LCT) into the above dialogue represents a practical means of providing multiple stakeholders with better grounded information so as to enable all the parties involved to make better decisions. A specific project example for this is included in the *Horizontal Issues* section of the Appendix.

Effective communication of the risks and benefits of new technologies

Both technical risk assessments, and perceived risks need to be discussed as early as possible amongst representative stakeholders. This facilitates constructive dialogue aimed at developing an understanding of the issues and influencing the research agenda. Such a dialogue also needs to encompass discussion on the risks and benefits of alternative technologies as well as the risks posed by a failure to adopt a new or specific technology.

A pan-European communication strategy

A key challenge in communicating the benefits and risks associated with novel technologies such as nanotechnology and biotechnology will be to manage the consistency and direction of 'messages' about these technologies. This will require a coordinated strategy at a European level. The HIG will develop a number of projects that will cover several objectives ranging from setting standards and disseminating best practice to providing information on safe handling and use of products. The aim will be to build trust across regions, encourage a better coordinated and more coherent European approach, and contribute to the ultimate goal of ensuring best practices are applied on a Europe-wide basis.

Cooperation with other technology platforms on common issues of concern
Increased cooperation amongst Technology Platforms facing similar concerns is being looked at to work on synergies in joint project proposals or alternative approaches in enhancing public understanding of new technologies.

Risk assessment and management strategies

The development of credible risk assessment and management strategies for new technologies is part of the process of addressing stakeholder concerns.

Regulatory decision support framework
In order to facilitate the introduction of new products onto the EU market it will be important to contribute to a more joined-up strategy with respect to EU-wide regulatory processes. The establishment of an Integrated Decision Support Framework for regulatory health, safety and environment (HSE) assessment of SusChem products and processes, within the REACH environment, will assist in this regard. Central to such a system is the development of targeted intelligent risk assessment and management strategies.

Past risk management approaches have often dedicated a disproportionate level of resources to hazard assessment and insufficient effort to the ultimate goal which is how best to achieve an appropriate level of risk reduction. The set up of SusChem will enable better alternatives to be developed. One such approach would be to target resources where exposure to risk is most likely to occur. Such problems are particularly faced by small and medium enterprises (SMEs) with limited resources and should therefore represent a priority in terms of issues to be addressed.

New technologies will raise new concerns which may require new testing strategies. The Joint Research Centre in cooperation with industry and other bodies such as the European Convention on the Protection of Animals (ECOPA) is already working to develop alternatives to animal testing. Industries' developments in advanced computational (*in-silico*) modelling will further support more efficient screening and testing of new products.

Many aspects of this issue are being brought together under an EU Commission sponsored "Alternatives Platform".
Any HIG activity in this area would not compete with this, as our goal is to complement such existing initiatives and focus on the new technology aspects that fall outside the existing initiative.

Support for innovation

R&D and innovation is essentially based on two main resources: smart and ambitious researchers and innovators; and a sufficient supply of funding. Both of these areas currently present a particular problem for chemical innovation in Europe and need to be tackled.

Education, skills and capacity building

Background

The availability of a skilled labour force is essential to the long-term viability and innovative capacity of the European chemical industry.

The challenging target of ensuring the highest possible standard of skills at all levels of the chemical industry and research necessary to support society's economic, ecological and social needs, requires many different kinds of actions. Some of the steps needed are short-term, but education and skills development as well as capacity building also require long-term and long-lasting input and activity from SusChem stakeholders.

Societal drivers

Many societal drivers call for concerted SusChem efforts in the area of education, skills and capacity building. There are serious concerns that the number of chemistry graduates across Europe has been in decline for a decade. The medium and long-term effect of this decline will impact all areas of research and development in the European chemical industry. Without an adequate supply of appropriately trained researchers and innovators an insufficient share of technologies targeted by SusChem may be realised within Europe.

In the recent years, companies have not signalled substantial recruitment needs. However, when industry is determined to invest in developing SusChem technologies, researchers and other professionals will need to master the new technologies not only within companies but also in research institutions.

Life-long learning is also an essential component of the current working life. This is well understood in industry. The European Union already emphasises the importance of continuous learning as one of the means for Europe to achieve its competitiveness goals. Within the chemical industry this means that, as new technologies are introduced, whole sectors of the workforce will need to continually keep their skills and knowledge up to date.

Meeting skills demands of chemical industry

All levels of education play a part in the SusChem framework. Primary and secondary education's role is to build the base for scientific understanding and to raise young people's interest in the sciences. Universities have to be able to attract young talented students to their programmes and to offer courses meeting SusChem's skills needs. Education and training institutions at all levels need access to information about the chemical industry's expectations and educational demands in order to serve the SusChem stakeholders in the best possible way.

Education and training institutions have an important role in ensuring the future skills, but in addition industry's actions are crucial in developing the skills and competencies of personnel to meet SusChem's needs. Investment in in-service training and relevant life-long learning opportunities are needed, in order to develop skills at all levels within companies. Indeed with the aging workforce, the role of in-service training becomes increasingly important in the future.

To better meet the challenges outlined by the stakeholders of SusChem, the following questions need to be answered:

- How many people already work in the technology areas targeted by SusChem?
- What are the recruitment plans and needs in industry?
- What kind of skills is needed in the future for innovation in the SusChem technology areas?
- How are universities and other institutions able to respond to these future needs?
- How could the platform support industry and educational institutions in sustaining and developing the skills base of the industry?

Experience in skills foresight exercises has shown that it is difficult to find detailed information about future skills needs for specific technology areas. However, SusChem has to establish as deep an understanding as possible on how education and training systems and company actions should and could support the development and application of the SusChem technology areas. Thus, despite the potential difficulties, this topic needs to be studied in the platform via a survey.

When using the results of this survey, special attention will be paid to the following European aspects:

- As academic education is undergoing a transformation throughout Europe (the Bologna process[17]), SusChem should give special attention to this process in order to ensure that there is adequate educational basis covering the SusChem technologies.
- Based on the results of the survey, the platform should also examine the possibilities offered by the Leonardo da Vinci programme, and other European initiatives, that could provide a basis for developing vocational training and lifelong-learning opportunities to meet the SusChem needs.

Motivating skilled young people

It is essential for the success of the platform to convince talented young people to make a career choice in favour of chemistry and the other sciences that will underpin Europe's future. Individuals' career preferences are formed at a young age. Even in primary school children have clear perceptions about industry, science and work in industry, and it has been shown that a well-planned education-industry partnership has a remarkable positive impact on these perceptions. Numerous ongoing actions at local, national and European level aim at improving the image of the chemical industry among children and young students. As these actions achieve their goals, they will also benefit SusChem and help to align its broader stakeholder base with the goal of sustainable chemistry.

SusChem projects in education, skills and capacity building

There are numerous ongoing projects and initiatives already underway in Europe that aim at developing education and training to meet industry's needs. They will provide useful information and input for SusChem. The platform itself will particularly invest in such actions where there is clear added value to be gained by cooperation within the platform. A specific SusChem effort is needed to survey this situation from the perspective of the three technology areas. A proposal for undertaking this survey is presented in the appendices. Further actions on education, skills and capacity building of SusChem will be planned based on the results of the survey.

In addition to specific SusChem projects, the platform will network with European chemical and educational organisations and other European Technology Platforms to combine actions where objectives coincide.

The HIG will also look at relevant SusChem aspects to existing studies related to the mobility of students and researcher between universities and companies, the availability of postgraduate education and vocational training.

Other proposed projects improving support for innovation in sustainable chemistry

Increasing effective stimuli for innovations whilst reducing potential barriers will be an ongoing challenge for technology platforms. Learning by doing and the sharing of best practices will be important elements of our eventual success. The proposed projects in the *Horizontal Issues* section of the Appendix represent some concrete examples of how our networks plan to contribute to this goal. All these projects will evolve based on stakeholder feedback, participation and support.

As SusChem develops an implementation action plan based on the platform SRA, the need for other cross-cutting projects will become apparent. The HIG will identify these needs and where it can, make a meaningful contribution to develop project proposals to meet them.

In addition, a number of other areas for project development, which as yet have not been fully worked up, have been proposed. They are listed here as an indication of additional areas in which the HIG's efforts may be focused as SusChem responds to the wishes of its stakeholders in the future.

Possible areas for future project work include:

- Development of a SusChem database based on real-world examples of sustainable chemistry.
- Actions to leverage the voice of the SMEs for chemistry innovation within the EU.
- A study of financial support models for start-up companies in chemistry and industrial biotechnology. The nature and image of our products requires a differentiated approach to venture capital sources as well as special roles via institutions such as the European Investment Bank (EIB) and the European Investment Funds (EIF).
- An investigation of new mechanisms for industry-academia research collaborations.

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SusChem
European Technology Platform For
SUSTAINABLE CHEMISTRY

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