Research Agenda for Process Intensification

Towards a Sustainable World of 2050

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Creative Energy
Energy Transition

Executive summary

Humanity is being confronted with several crucial challenges within the next 50 years, including shortage of energy, material resources, water, food, environmental pollution and ageing society. Process industry can significantly contribute to master theses challenges, but it needs to make a structural change. Process Intensification (PI) is a very important vehicle to facilitate this process. It is defined as a set of often radically innovative principles ("paradigm shift") in process and equipment design. The objective of this research agenda, sponsored by the Action Plan Process Intensification of the Dutch Institute for Sustainable Process Technology, is to highlight research topics in PI that should be started in the short term to realise the technological milestones that will be vital to 2050 and beyond in four selected areas (health, transport, living, and food & agriculture). The research agenda is the result of a unique backcasting process based on concrete science through the participation and supporting analysis of a group of over 75 leading European scientists, industrialists and science managers. The team defined a set of key technological achievements ("milestones") that must be reached by the year 2030. The main section of this document contains the research topics for each milestone. Collectively, these research topics lay the necessary foundation for the technological achievements that need to be realised to reach a sustainable world by 2050. Scientific background of the Agenda will be published in a special issue of the Elsevier journal *Chemical Engineering and Processing: Process Intensification* at the beginning of 2012.

The agenda addresses improved and small-scale processes for production of goods through better control of molecule interactions, the recovery of rare elements and composite materials, better methods for water supply and food processing, development of personalized medicine and bio-hybrid organs, energy generation, storage and distribution, and converting sunlight to fuels. Each chapter of the agenda explains the rationale of the milestone, gives a short overview over current technologies and addresses their shortcomings, shows how to progress in the field and postulates research activities needed in the next 5 years, describes the expected deliverables and indicates the disciplines involved in each deliverable.

The research agenda is primarily intended as a recommendation from an international team of leading scientists to political, economic and scientific organisations for the funding of key multidisciplinary R&D programs including not only Process Intensification and process technology but also interfacing disciplines, such as chemistry, biochemistry, applied physics, materials engineering and electronics.

Contents

A. Introduction

The process industry plays a central role in society. It supplies the building blocks of the answers to society's needs, such as materials that form products, provide energy, and feed and cure people. In many countries, the process industry is also a significant part of the economy in terms of contribution to GDP and employment, and the industry is a major consumer of energy and resources.

With a growing population and an increasing awareness of the world's unsustainable waste and use of energy and resources, the process industry must look towards making a structural change. To do so, Process Intensification (PI) will be essential. Process intensification is defined as a set of often radically innovative principles ("paradigm shifts") in process and equipment design. Such principles can yield significant benefits in terms of process and chain efficiency, capital and operating expenses, quality, waste, process safety and more. Process intensification addresses the need for energy savings, CO_2 emissions reduction and enhanced cost competitiveness throughout the process industry. It will therefore contribute significantly to the competitiveness of process industries worldwide by making industrial processes faster, more efficient and less damaging to the environment.

Several programs exist in Europe to advance Process Intensification across industries, such as the Action Plan Process Intensification (APPI). The European Commission has also recognised the importance of PI and addresses this issue in the current Framework Programme. The time horizon for technologies developed in these programs is typically as much as ten years in the future. Many of these technologies will be of significant value, from both economic and environmental perspectives. Nevertheless, society's needs beyond the horizons of these programs are paramount, and solutions to these needs must be based on technological principles that have yet to be developed.

The objective of this research agenda is to highlight research topics that should be started in the short term to realise the technological milestones that will be vital to 2050 and beyond. The research agenda is the result of a unique backcasting process based on concrete science through the participation and supporting analysis of a group of over 75 leading European scientists and science managers.

B. Delft Skyline Debates

A visionary project with a solid scientific basis

The Delft Skyline Debates was a unique visionary international project centred on the current and future process industry. The Debates were carried out between December 2009 and June 2010, coordinated by the Delft University of Technology and sponsored by the Action Plan Process Intensification of the Dutch Institute for Sustainable Process Technology. The Debates' objective was to develop a scientific vision of long-term development (beyond 2050) in the field of process technology in general and Process Intensification in particular and to identify the short-term research required to realise this vision.

No other vision of the distant future has used such a solid scientific basis for identifying specific research topics at the shorter term. A multidisciplinary team of 75 prominent scientists, young researchers and science managers from 13 countries representing leading universities, research institutes, industries, R&D funding organisations and European Commission was assembled (Table 1). The team chaired by Professor Andrzej Stankiewicz from Delft University of Technology included both academics and industrialists known for their visionary thinking and ability to look beyond the horizons of current R&D trends. Their quality and diversity – with backgrounds ranging from healthcare and green chemistry to oil – provided an exceptional point of departure for defining the international research activities that will ultimately shape the sustainable world of 2050. The participating experts worked together during two two-day workshops and in virtual teams between these workshops. The process was facilitated by Roland Berger Strategy Consultants.

Table 1: Overview of participants and contributors to the Delft Skyline Debates.

Participant/contributor	Affiliation
Adisa Azapagic	University of Manchester
Ton Backx	Eindhoven University of Technology
Augustinus Bader	Leipzig University
Giuseppe Barbieri	University of Calabria
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Andrzej Górak	Technische Universität Dortmund
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Josep M. Guerrero	Technical University of Catalonia, Barcelona
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Dieter Hofmann	Helmholtz-Zentrum Geesthacht
Andrew J. Hunt	University of York
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Jan Janssen	Agentschap NL
Sascha R. A. Kersten	University of Twente
Jos Keurentjes	AkzoNobel Industrial Chemicals

Participant/contributor	Affiliation
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Pieter Kuiper	Auto Recycling Nederland, Amsterdam
Masaru Kurihara	Toray Industries Inc, Chuo-ku
Richard Lakerveld	Delft University of Technology
Young M. Lee	Hanyang University, Seoul
Andreas Lendlein	Helmholtz-Zentrum Geesthacht
Hans van Luijk	Platform Chain Efficiency
Francesca Macedonio	University of Calabria
Wolfgang Marquardt	RWTH Aachen
Helmut Mothes	Bayer Technology Services
Jacob Moulijn	Delft University of Technology
Guido Mul	University of Twente
Bettina Muster	AEE INTEC, Gleisdorf
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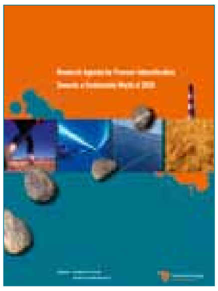
Helen L. Parker	University of York
Lucie Pfaltzgraff	University of York
Norbert Radacsi	Delft University of Technology
Andreas Rickert	Bertelsmann Stiftung
Philipp Rudolf von Rohr	ETH Zürich
Fransisco J. Rossier-Miranda	Wageningen University
Johan Sanders	Wageningen University
Christian Schacht	Delft University of Technology
Gerhard Schembecker	Technische Universität Dortmund
Hans Schnitzer	Graz University of Technology
Tim Seifert	Technische Universität Dortmund
Rafi Semiat	Technion – Israel Institute of Technology, Haifa
Stefan Sievers	Technische Universität Dortmund
Andrzej Stankiewicz	Delft University of Technology
Georgios Stefanidis	Delft University of Technology
Wim van Swaaij	University of Twente
Peter Verheijen	Delft University of Technology
Jose-Lorenzo Valles	European Commission
Dionisios G. Vlachos	University of Delaware
Rein Willems	Netherlands Chemical Industry Association
Hans de Wit	Delft University of Technology
Chieh-Chao Yang	University of Twente
Yongxiang Yang	Delft University of Technology

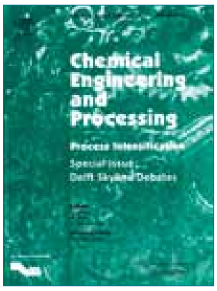
Research for a sustainable world in 2050

The topics of this research agenda present key initial steps towards a sustainable world in 2050. They are the result of a coherent process that started with the identification of beacons and milestones (Figure 1).

Figure 1: The Delft Skyline Debates followed a three-step backcasting process. Reports were published upon the completion of each step.

Timeline	2017	2030	2050 →
Skyline steps	3	← 2	← 1
Skyline results	**Research Topics**	**Key PI Milestones**	**Beacons**
	PI objectives that should be achieved by 2017 in order to realize the key milestones	**Technological achievements** in process intensification that should be accomplished by 2030 in order to reach more than one of the beacons of 2050 and that is particularly challenging to achieve	**Aspired state of the world in 2050** within a specific theme for a specific group of people
Deliverables	**Research Agenda**	**Special Scientific Issue**	**Delft Skyline Times**
	> Proposed research topics based on position papers	> Collection of scientific position papers	> Popular description of "beacons" for PI research





The Delft Skyline Debates began with the development of a view of the world in the year 2050. Inspired by guest speakers, the participants identified beacons in four selected areas (health, transport, living, and food & agriculture), with each beacon describing an aspired state of the world. Three “Boundary beacons” set the high-level boundary conditions that hold true for all areas. These boundary conditions are related to energy, waste and resources. Figure 2 and figure 3 present an overview of the beacons. Short descriptions of each beacon are included in the appendix. One example of a beacon, “Plants replace mineral mines”, addresses the fact that traditional resources of almost half of all elements will be depleted within about 50 years. However, approximately 50% of the elements we use can be obtained from agriculture, provided that we develop biorefineries that optimise biomass utilisation through advanced extraction and other separation techniques.

Figure 2: The participants identified beacons in four categories for the year 2050.

Health	For the first time in history…
Everybody healthy!	> A large class of diseases have been eliminated by prevention and cure for a worldwide population, leading to a life-expectancy of 100
Better health by personalized food!	> All people can diagnose their dietary needs for the day and buy personalize diets
When I'm ninety four….	> The quality of life is so improved that life expectancy is equal for all new-born babies irrespective of the place of birth and that health is excellent throughout people's lifes
Transport	**For the first time in history…**
Transport – it's electric	> All land-based transport runs on electric energy based on a sustainable electricity network and/or decentralized chemical conversion system
Cars from waste	> The transport sector is completely sustainable – all cycles are closed including in materials and resources
Living	**For the first time in history…**
Produce where you consume!	> Most consumer products are produced in close proximity to the user from raw materials from the proximity
Power House	> 90% of the houses produce more energy than they consume, and have doubled their lifetimes
Food & Agriculture	**For the first time in history…**
Plants replace mineral mines	> We can obtain 50% of all elements we use from agriculture
Good food for all!	> We will have achieved efficient and sustainable, closed-cycle production, harvesting and conversion of food, from field to consumer for every human being on earth, with a total efficiency of >50% in energy, and no waste or emissions
Food with less energy input	> The integral energy efficiency of food production reaches 20% worldwide

Figure 3: The pathways to the aspired beacons have to meet the conditions set by three "Boundary beacons".

Boundary Beacons	For the first time in history…
Energy	> We are able to produce chemicals on a commercial scale using exclusively solar, geothermal or wind energy
Resources	> We have managed to eliminate fully the use of non-renewable raw materials (including catalysts) in chemical processes (without competing with food on biomass)
Zero waste	> All chemical and food processes are zero waste

To illustrate the aspirations of the participants, the beacons were converted into newspaper articles that one might expect in the year 2050. The result is the "Delft Skyline Times" of June 4, 2050 (see below).

Figure 4: One of the articles in the Delft Skyline Times of June 4, 2050 covers the role of biomass in the EU economy.

Two thirds of European biomass through Port of Rotterdam-Antwerp

Irene Bol
Rotterdam

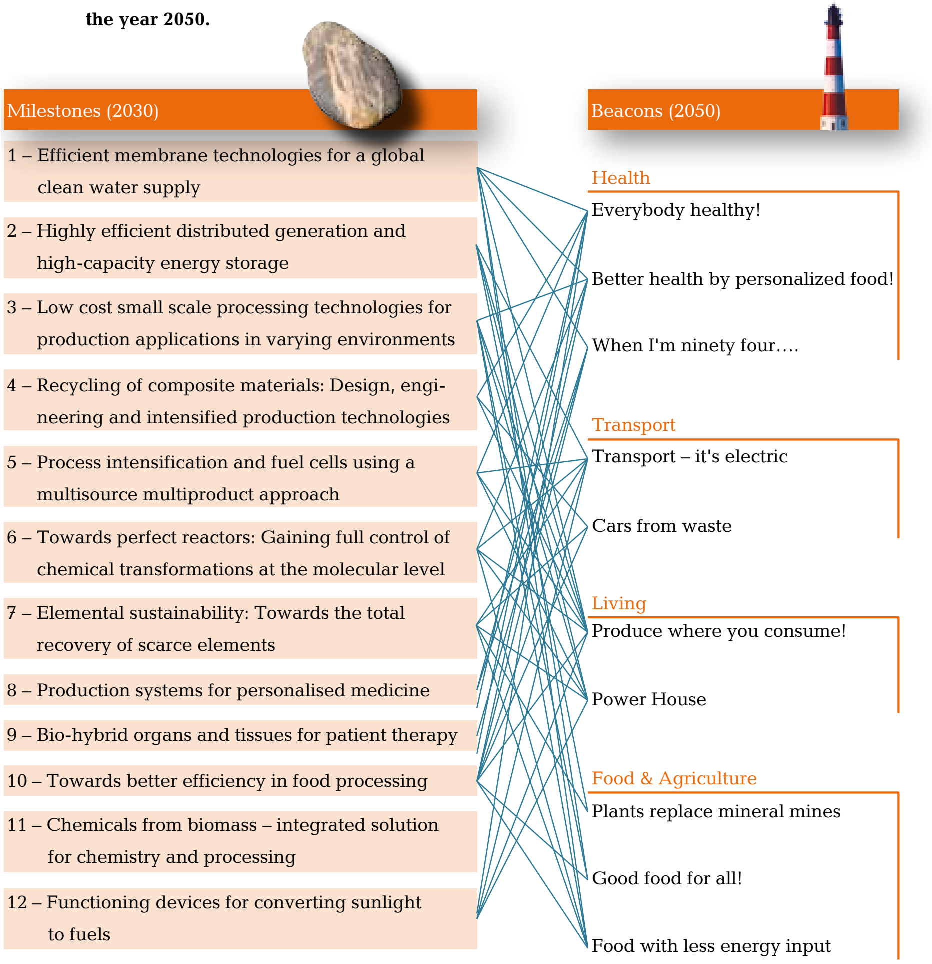
The Port of Rotterdam-Antwerp, the largest biomass hub in Europe, last year handled more than two thirds of all European biomass. About 40% was processed locally, in the biorefineries on the Second and Third Maas Plains, the gasification installations and retrofitted oil refineries at Pernis and smaller, specialized production sites in Delft and the city of Rotterdam. The rest mostly found its way to the chemical and energy industry in the Netherlands, Germany and France.

Total biomass imports into the European Union totaled 270 million tons of oil equivalent (Mtoe) in 2049. Most of it came from North America, Brazil and Ukraine (forestry biomass) and the Mediterranean (algae). About 240 Mtoe was produced in the EU itself. Biomass processing, logistics and transit trade amounted to approximately 10% of Dutch GDP.

PAGE 11 Hub, Holland, Hub. How a small country became the world's leading biobased economy.

Guided by the beacons of 2050, the team subsequently defined a set of key technological achievements ("milestones") that must be reached by the year 2030. A main criterion for a milestone was that each must contribute to reaching several beacons. This criterion ensures that milestones are relevant to the vision and can be widely applied. Figure 5 lists the milestones and their links with beacons. Whereas beacons can be clearly linked to societal needs in 2050, milestones have much more of a technological component. In the period between the two Delft Skyline Debates workshops, small groups of participants described the relevance of each milestone and the associated scientific challenges in a collection of scientific position papers.

Figure 5: The Delft Skyline Debates led to 12 milestones in 2030 that are linked to several beacons for the year 2050.



The milestones, and in particular the specific scientific challenges associated with them, led to the identification of research topics for process intensification technologies for the next five years. In the second workshop, participants further enhanced and challenged the research topics put forth by the groups that had prepared the milestone position papers. In this way, the research topics benefited from the many disciplines and extensive expertise represented.
The introductions to the research topics (next section) include brief descriptions of the milestones.

The main section of this document contains the research topics for each milestone. Collectively, these research topics lay the necessary foundation for the technological achievements that need to be realised to reach a sustainable world by 2050.

C. Research Agenda

Introduction

The following chapters describe twelve key technological achievements ("milestones") for 2030 identified during the Delft Skyline Debates. It is expected that process technology, in general, and Process Intensification, in particular, should significantly contribute to reaching each milestone. While examining the milestones, several interesting observations can be made.

First, in the coming decennia, Process Intensification will operate not only within its traditional domain, i.e., the manufacturing of chemical products, but it will also play a more important role in the development of new breakthrough technologies that address crucial societal problems, such as human health, the availability of water and food, energy and material resources, transport, and living standards. This trend is already clearly seen as young process technologists find jobs and work on intensified devices and processes in such sectors as electronics, biomedical, and automotive.

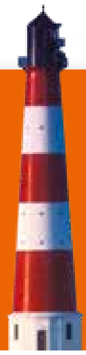
Second, all of the identified milestones appear relevant to the realisation of more than one beacon for 2050, with the vast majority of them addressing all three "boundary" beacons, i.e., Energy, Waste and Resources. This relevance is presented in detail in Table 2.

Third, strong relations between different milestones can be seen, as presented in Table 3. For each milestone, several research topics have been defined that should compose a research agenda for Process Intensification and process technology in the next five years.

The research agenda is primarily intended as a recommendation from an international team of leading scientists to political, economic and scientific organisations for the funding of key multidisciplinary R&D programs including not only Process Intensification and process technology but also interfacing disciplines, such as chemistry, biochemistry, applied physics, materials engineering and electronics.
Most milestones included in this Research Agenda have been analysed and are described in more detail in a series of full-size scientific papers that will be published as a special issue of the Elsevier journal *Chemical Engineering & Processing: Process Intensification*. The special issue is expected to be available in 2012.

Andrzej Stankiewicz
Chairman of Delft Skyline Debates

Table 2: Relevance of the identified technology milestones for the 2050 beacons.

Category	Beacon 	1 – Efficient membrane technologies for a global clean water supply	2 – Highly efficient distributed generation and high-capacity energy storage	3 – Low cost small scale processing technologies for production applications in varying environments	4 – Recycling of composite materials: Design, engineering and intensified production technologies
Health	Everybody healthy!	•			
	Better health by personalized food!	•		•	
	When I'm ninety four….	•			
Transport	Transport – it's electric		•		
	Cars from waste				•
Living	Produce where you consume!	•	•	•	•
	Power House		•	•	
Food & Agriculture	Plants replace mineral mines		•		
	Good food for all!	•		•	
	Food with less energy input	•		•	
Boundary	Energy	•	•		
	Resources	•	•		
	Zero Waste	•	•		

	5 - Process intensification and fuel cells using a multisource multiproduct approach	6 – Towards perfect reactors: Gaining full control of chemical transformations at the molecular level	7 – Elemental sustainability: Towards the total recovery of scarce elements	8 – Production systems for personalised medicine	9 – Bio-hybrid organs and tissues for patient therapy	10 – Towards better efficiency in food processing	11 – Chemicals from biomass – integrated solution for chemistry and processing	12 – Functioning devices for converting sunlight to fuels
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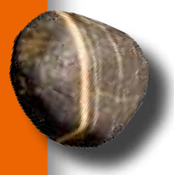
Table 3: Relations between the individual Delft Skyline Debates milestones.

	Category	1 – Efficient membrane technologies for a global clean water supply	2 – Highly efficient distributed generation and high-capacity energy storage	3 – Low cost small scale processing technologies for production applications in varying environments	4 – Recycling of composite materials: Design, engineering and intensified production technologies
1	Efficient membrane technologies for a global clean water supply		•	•	
2	Highly efficient distributed generation and high-capacity energy storage	•		•	
3	Low cost small scale processing technologies for production applications in varying environments	•	•		
4	Recycling of composite materials: Design, engineering and intensified production technologies				
5	Process intensification and fuel cells using a multisource multiproduct approach	•	•		
6	Towards perfect reactors: Gaining full control of chemical transformations at the molecular level		•	•	
7	Elemental sustainability: Towards the total recovery of scarce elements		•		•
8	Production systems for personalised medicine			•	
9	Bio-hybrid organs and tissues for patient therapy				
10	Towards better efficiency in food processing	•		•	
11	Chemicals from biomass – integrated solution for chemistry and processing		•	•	
12	Functioning devices for converting sunlight to fuels		•	•	

	5 - Process intensification and fuel cells using a multisource multiproduct approach	6 – Towards perfect reactors: Gaining full control of chemical transformations at the molecular level	7 – Elemental sustainability: Towards the total recovery of scarce elements	8 – Production systems for personalised medicine	9 – Bio-hybrid organs and tissues for patient therapy	10 – Towards better efficiency in food processing	11 – Chemicals from biomass – integrated solution for chemistry and processing	12 – Functioning devices for converting sunlight to fuels 
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1 Efficient membrane technologies for a global clean water supply

Background – Why This Milestone

Currently, the availability of potable water has undoubtedly become a worldwide problem due to the continuous growth in water demand that is not balanced by adequate recharge. The most obvious advantages of improved technologies for clean water production are as follows:

- The enhancement of water availability for domestic, agricultural, industrial and tourism development
- Higher recovery factors leading to zero-liquid-discharge processes
- The reduction of energy consumption, which is responsible for ~40% of current desalination costs
- The manufacturing of by-products from waste streams from current desalination plants

The Milestone is necessary to verify if significant improvements in the solution of the existing problems will be reached. In particular, the possibility of minimising the brine disposal problem and increasing the recovery factor via membrane crystallisation and membrane distillation needs to be confirmed.

Current State-of-the-Art

Water shortages have become a major problem worldwide, which negatively affects human life and the sustainable development of our society. The prospect of severe water shortages stresses the need for new strategies in the field of water resources and water supply management. Undoubtedly, water reuse and sea/brackish water desalination emerged in the last decades as the most promising contributions to solve the problem. Membrane technology, and in particular Reverse Osmosis (RO), with its intrinsic characteristics of efficiency and operational simplicity, high selectivity and permeability for the transport of specific components, compatibility between different membrane operations in integrated systems, low energy requirement, stability under operative conditions, environment-compatibility, easy control and scale-up, and large flexibility, is today the dominant technology in water desalination contributing approximately 50% of the world's desalination capacity. Despite this great success, some critical problems still remain: reduction in the unit water cost, improvement in water quality, enhancement of the recovery factors in high-pressure membrane systems, and minimisation of the brine disposal impact.

How to Progress

To reach the current milestone, the research efforts in the next 20 years should focus on the development of new and/or improved membrane technologies for global water supply:

- Optimisation and development of membrane technology and/or system design to achieve higher performance, flux and selectivity, with respect to new contaminants in water streams (such as organic and pharmaceutical compounds, and ions originating from electronics that often end up in landfills and contaminate land, water and air)
- Novel concentrate treatment options (such as membrane crystallisation) that will help in transforming the traditional brine disposal cost in a potentially profitable new market and in the development of inland brackish water RO
- Realisation, utilisation and expansion of carbon nanotube, aquaporin channels and new protein-based membranes
- Further development and proliferation of small and compact water desalination devices
- Development of water treatment systems coupled with renewable energy sources for a significant reduction in energy consumption
- Reconsideration of forward osmosis, pressure-retarded osmosis and reverse electrodialysis as membrane techniques to generate power from salinity gradients

- Supplying water of diverse quality to the final users depending on their requirements (drinking, washing, agricultural, irrigation and industrial use) through the use of parallel lines of distribution, each with an appropriate level of purification, and optimisation of the water distribution system through the use of specific software packages
- Management of integrated desalination and water reuse at least at the "city level"

Therefore, the development and improvement of technologies for a global clean water supply requires an integrated multidisciplinary and multiscale approach, from chemical engineering to chemistry, biology, microbiology, material science, electronics and advanced computing.

Research Activities Needed, 2017 Deliverables and Disciplines Involved

Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. Optimisation and development in membrane technology and system design	Development of experimentally validated mathematical models and commercial software for advanced integrated membrane systems in desalination	Chemical physics, materials engineering, electronics, chemical engineering, chemistry, advanced computer modelling and control systems
2. Novel concentrate treatment options	Industrial implementation of salt extraction systems from brine desalination plants. Zero liquid and solid discharge from desalination plants	Materials engineering, physics, biology, microbiology, chemical engineering, catalysis, advanced computer modelling and control systems
3. Water treatment systems coupled with renewable energy sources	Development of reverse osmosis and nanofiltration water treatment systems coupled with solar energy, wind energy and energy from salinity gradient	Materials engineering, physical chemistry, chemical engineering, advanced computer modelling and control systems
4. Energy production from salinity gradient	New industrial membranes and modules, minimisation of concentration polarisation in forward osmosis, pressure-retarded osmosis and reverse electrodialysis	Chemical physics, materials engineering, electronics, chemical engineering, chemistry, advanced computer modelling, advanced control systems
5. Development of small water treatment systems	Development of small-scale portable systems based on adsorption or membranes	Chemical physics, materials engineering, electronics, chemical engineering, chemistry, advanced computer modelling and control systems

2 Highly efficient distributed generation and high-capacity energy storage

Background – Why This Milestone

In the past decades, we observe a trend towards decentralised electricity production known as decentralised generation (DG). The main reason for this shift is the development of renewable energy technologies, such as wind turbines and solar photovoltaic panels, which convert locally available renewable energy into electricity. Sources of renewable energy are often distributed around the world rather than being limited to certain spots. With the development of distributed renewable energy conversion technologies, a shift from centralised to decentralised is occurring, and we should also take into account that renewable energy is a source of energy that is very different from fossil fuel sources because of its fluctuating and often unpredictable nature. This unpredictability causes additional problems for the transition of our present power generation system towards a more distributed generation of renewable energy. The often proposed and obvious solution for the fluctuating and discontinuous nature of renewable energy is storage. We will also discuss other options such as flexible co-production, the development of so-called smart grids, demand-side management and local production of chemicals and fuel.

Current State-of-the-Art

Currently, the decentralised energy production, also called distributed generation (DG), is an important topic, not only for research, but also in government and industry. With increasing use of renewable energy in the grid, electric power is distributed from central power plants to the end users and produced near the endpoints of the grid. However, the current electrical grid is not conceived to work bi-directionally, so it is necessary to change the philosophy of the electric system as a whole. The rules and policies have to be modified to accommodate distributed generation. This process is ongoing but not to the extent that is desirable and technically possible. For instance, if photovoltaic panels on the roof were connected to the grid by means of power electronics converters and there were to be a fault in the grid, then the converter must be tripped for security reasons. As a result, if a grid fault occurs on a sunny day, electricity will not be available, even if it can be produced with an individual's solar panels. This surprising situation occurs because systems are not allowed to operate in "island mode" in some countries. Additionally, an individual is not allowed to install batteries with the grid-connected photovoltaic system. However, many industrial and government projects are working towards "island operation" of parts of the grid, referred to as micro grids, and connecting car batteries to the grid in a so-called 'Vehicle to grid' (V2G), and smart grids in general. This contradiction is a symptom that the technology is now more advanced than the regulatory and grid codes, which must change soon to allow innovation towards a more sustainable sector. The decentralisation of energy production will possibly be linked to, for example, the decentralisation of the population and water treatment.

How to Progress

To reach the current milestone, the research efforts in the next 20 years should focus on the development of new technologies for operating the electric grid in order to deal with the incorporation of distributed generation from fossil energy and renewable energy sources. Where appropriate, the electric grid should be able to transport electricity in both directions connecting different places of net electricity consumption and net production that may vary depending on the circumstances.

Due to technological advances in power electronics and telecommunication systems, particularly those applied to micro grids and smart grid concepts, the distributed generation can be extended and supported by distributed storage and smart loads. Thus, in the future, we may see telecommunications infrastructure running together with the electrical infrastructure. Parts of the grid will be reconfigurable, and the information from the smart metres, generators and loads will flow to the nearest Agent. The Agent will be able to manage the micro grid area and interchange references and information with a Central Controller. It is expected that experience from the development of the Internet can be transferred to the development of smart grids and that the Internet itself can be useful in this respect. Presently, there is already a strong awareness that smart grids might provide a large part of the solution to accommodate distributed generation. In this concept, every house will have its own Agent that will control generation and storage and take care of the loads, trying to adjust the generation and consumption to reduce storage and make the system more efficient. The energy will be shared by a community of neighbours, and the grid will be formed by a number of small autonomous grids. The amount of power in transportation and distribution lines will be reduced because the energy will be balanced locally as much as possible.

With the introduction of solar panels, battery storage systems and fuel cells, the arguments for introducing DC systems instead of the present standard AC electric systems become stronger. However, what is the optimum system under different circumstances?

New energy storage devices will be customised depending on the needs. It is expected that not only in large-scale applications such as in so-called stranded wind, but also on a small scale, electricity that is not consumed or stored can be used to produce chemicals and fuel. These resources can most likely be produced by first generating hydrogen. Thus, storage can be viewed in a different light; it should include alternatives such as alternative use of the storage medium, for example hydrogen, and use of alternative fuels to generate electricity when needed in so-called multisource multiproduct energy systems. By enlarging the system boundaries, additional solutions can be found, and distributed generation should not only deal with the generation of electricity but also with the local production of chemicals and fuel. Smaller chemical units as developed in the process engineering R&D topic of ‘process intensification’ will enable these new options.

In general, distributed generation should be integrated into other developments and sectors following the different forms of integration.

Research Activities Needed, 2017 Deliverables and Disciplines Involved

Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. Conceptual design of connected and interconnected grid DG systems	Demonstration of interconnected (autonomous) micro- grids	Electrical engineering
2. Conceptual design of autonomous distributed generation systems	Demonstration of the superwind concept including solar and biogas in an autonomous village	Engineering [all disciplines]
3. Flexible production devices	Fuel cells with flexible capacity that can double their power output. PI of small-scale fuel reactors	Materials engineering, physics, chemical engineering, catalysis, advanced computer modelling
4. Superconductivity for storage and transport	Determination of the feasibility of a standalone superconducting storage unit for an office building	Physics, Engineering [all disciplines]
5. DC grids and DC/DC power converters	Determination of the feasibility of local DC grids with suitable DC/ DC power converters	Electrical engineering
6. Conceptual design of connected and interconnected grid DG systems	Demonstration of interconnected (autonomous) micro- grids	Engineering [all disciplines]
7. Conceptual design of integrated distributed generation systems following the seven forms of integration mentioned in the paper	Development of a number of new integrated concepts that are worth exploring further in a feasibility study	Engineering [all disciplines]
8. Development over regulatory framework for the integration of distributed generation.	Implementation of suitable regulation for at least demonstration projects but preferably also for real life implementation of larger scale distributed generation	Policy studies

3 Low cost small scale processing technologies for production applications in varying environments

Background – Why This Milestone

During the past decades, chemical products have become increasingly diverse, resulting in an expanding volume of specialty chemicals. As these products are currently manufactured in batch mode, which is very inefficient, new continuous small-scale production technologies are needed to increase production efficiency. The food and biofuel industry, with their distributed agricultural feedstocks and small-scale processing technologies, can also increase process efficiency. In particular, the removal of water and waste before transportation of the intermediate products to centralised processing plants can make processes more efficient. Furthermore, production of storable intermediates will increase the utilisation of capital-intensive processing plants that can only be operated according to the seasonal availability of the agricultural raw material if state-of-the-art production technology is applied. However, the economy of scale and increasing labour costs with decreasing production capacity hamper the application of distributed production technologies. This hurdle can only be overcome by developing new efficient small-scale processes and flexible small-scale equipment for application to various process conditions, including necessary process control technologies.

Current State-of-the-Art

In the current chemical production technology, usually either large-scale continuous or small-scale batch production is applied. On the one hand, large-scale continuous processes are capable of producing a very specific product with a rather low specific energy consumption and personnel demand, leading to low production price. However, this type of plant is inflexible, and a huge local capital investment is necessary. Batch production facilities, on the other hand, are suitable for small-to-medium production capacities and can easily be adapted in terms of processing time and product changeover. They are thus much more flexible than large-scale continuous plants. Unfortunately, the lack of energy integration options and the necessity for periodic cleaning, especially in the case of changing the product being processed, makes batch-processing plants very inefficient.

In the food industry, much of the processing is performed in decentralised plants. However, as crops are usually available over distributed areas and during certain time periods, small-scale processing equipment is needed for initial processing steps. In the small scale, hygiene restrictions and the fact that most operations in food processing are not continuous result in frequent cleaning, which causes an increased demand in manpower. Energy recovery is difficult because the processes are not continuous, which means that heat sinks are not available at the same place and same time. Furthermore, available energy is often stored in solids, from which heat transfer is difficult.
As in food processing, the raw material is distributed in biofuel production. Because high-value chemicals from plants and biofuels are currently produced in large-scale factories, the environmental and economic impact in the case of an accident is enormous and transportation costs are high, primarily due to water content and the need to recycle minerals back into agricultural fields. With crops only growing seasonally, supply according to demand is still a problem.

How to Progress

To reach the focused aims in chemical, food and biofuel production, process intensification provides the necessary methods and concepts. New conversion processes must be developed that are highly energy efficient, selective and versatile with regard the feedstock. In the chemical industry, the product life cycle becomes shorter due to the development of new processes, and engineering and construction concepts need to be redeveloped. In the case of biofuel production, the processing of highly functionalised biomass molecules in multiphase environments is extremely complex. To drastically improve the efficacy of several inefficient processing routes, several reactions and functions should be coupled in an optimally designed single unit. Furthermore, reactive processes should be designed such that the need for complex, expensive and energy-demanding separation and purification steps downstream are minimised.

For economically and environmentally viable operation of small-scale chemical, food and biofuel production facilities of the future, new processing equipment will be needed. Moreover, besides turning batch processes to continuous processes, operating at lower temperatures and using waste energy will increase process efficiency in all addressed industries. Furthermore, production processes based on agricultural products will be split in two parts: one close to the fields to obtain intermediate products in small-scale processing plants at low costs, and the other in central large scale factories, where the final process steps are run.

To overcome the economy of scale issue, modularisation should be applied broadly. Modularisation will lead to an increasing number of factories and apparatuses produced and, thus, to significantly falling equipment prices. As personnel costs increase when production capacities decrease, plant owners will need to operate their own plants. Process optimisation and control strategies for this new situation must be developed to make process equipment intuitively operable. For batch processes not suitable for the conversion to continuous operation, high-efficiency energy storage technologies have to be developed for heat recovery and for the integration of renewable, but intermittent, energy. To convince process owners to apply flexible small-scale equipment, the economic viability of the new concept must be shown.

Research Activities Needed, 2017 Deliverables and Disciplines Involved

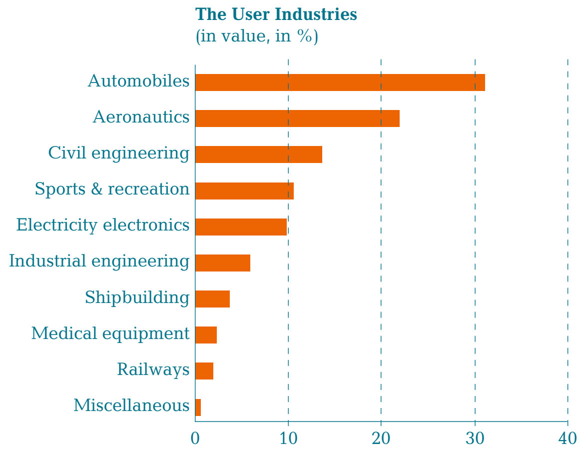
Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. Integrated biorefining processes combining several global reaction steps in a single reactor and/or several functions in a single equipment unit (hybrid/multifunctional processes)	Two to three new process concepts developed with proof-of-principle on laboratory scale	Materials engineering, chemical engineering, process engineering, chemistry, advanced computer modelling
2. Modularised equipment in terms of raw material, process conditions and throughput	Two to three concepts developed with proof-of-principle on laboratory scale	Materials engineering, chemical engineering, process engineering, chemistry, advanced computer modelling
3. Application examples for modularised process equipment	Five to six example processes with great industrial relevance => analyse and demonstrate potential of equipment reusability	Chemical engineering, process engineering
4. Strategies for modularisation of process equipment	Modularisation concept available, basing on process examples identified in 3.	Chemical engineering, process engineering, advanced computer modelling
5. New process design methodologies based on modularised process equipment	Process design method established for at least one case study	Chemical engineering, process engineering, advanced computer modelling
6. Economic evaluation of new modularised production concepts	Techniques for cost estimation of small-scale modular process equipment (example: equipment identified in 3.)	Cost engineering, plant engineering, supply chain management
7. Low temperature processes replacing current high temperature technologies	Two to three concepts developed with proof-of-principle on laboratory scale	Chemical engineering, process engineering, chemistry, catalysis, advanced computer modelling
8. Equipment suitable for first processing near raw material deposit	Two to three examples for early raw material processing steps	Chemical engineering, process engineering, advanced computer modelling
9. Socioeconomic impact of integrating local feed stock producers into global supply chain	Two to three examples for early raw material processing steps including subsequent supply chain to final product	Cost engineering, plant engineering, supply chain management, advanced computer modelling

4 Recycling of composite materials: Design, engineering and intensified production technologies

Background – Why This Milestone

Composite materials provide design engineers with superior quality and a long lifespan. Generally speaking, three types of composite materials are widely used in various types of applications: (1) polymer-matrix composites (PMC), (2) metal-matrix composites (MMC), and (3) ceramic-matrix composites (CMC). Globally, approximately 10 million tons of composite materials are produced annually (PMC type), of which 30% is based on thermoplastics and 70% is based on thermosets. Furthermore, other types of composites are produced in lesser amounts, such as metal matrix and ceramic matrix composites. According to Chalaye [1], the largest market of composite materials is North America (47%), followed by Europe (28%) and Asia (23%) in 2000 (total production of 7 million tons). The two major application sectors (based on value) are the automotive industry (over 30%) and the aerospace industry (over 20%). Figure 6 shows the usage of composite materials estimated for year 2000.

Figure 6: Application of composite materials



Recycling of engineering materials contributes to the sustainability and sustainable development of industrial processes. Currently, metals, glass, paper, and thermal plastics are recycled to a great extent. However, composite materials, which are in a special category of engineering materials, are not yet properly recycled (both the matrix and reinforcement materials), mainly due to their inherent heterogeneous nature (the matrix and reinforcement), and poor material recyclability, in particular, the thermoset-based composites. The current and future waste management and environmental legislations require all engineering materials to be properly recovered and recycled from End-of-Life (EOL) products, such as End-of-Life Vehicles (ELVs). Recycling will ultimately lead to resource and energy savings for the production of reinforcement and matrix materials.

[1] Hervé CHALAYE, Composite Materials: drive and innovation. Le 4 Pages, des statistiques industrielles, Nº 158 - February 2002 (www.insee.fr/sessi/4pages/pdf/4p158anglais.pdf).

Current State-of-the-Art

Currently, there are limited commercial recycling operations for main-stream composite materials due to technological and economic constraints. Composite recycling is hindered by both the fibre and reinforcement, and by the matrix or binders, in particular thermoset binders. Because of these challenges, most of the recycling activities for composite materials are limited to the down recycling, such as energy or fuel recovery with very little materials recovery, e.g., reinforcement fibres. However, these activities must be expanded to true materials recycling according to future environmental legislations such as EU Directives for End-of-Life Vehicles (ELVs).

Recycling of composite materials involves two distinct aspects. First, the composite scrap could be ideally reshaped into new composites after mechanical separation. This is a type of reuse. Second, the composite scrap could be decomposed into new matrix and new reinforcement materials, or at least one of these constituents. When either option is not possible, the energy recovery from organic-bearing composites (PMCs) should be the last choice through combustion and pyrolysis. It is arguable whether this last option is regarded as materials recycling; however, at least energy could be recovered. The first type of recycling, from EOL composites to new composite scrap, is very limited and feasible only for the thermoplastic matrix composites due to their plasticity and re-formability. It cannot be applied to the composites based on thermosets, metal and ceramics as matrix materials. For materials recycling, we also differentiate between the new scrap (which comes directly from the manufacturing process) and old scrap (or post-consumer scrap). Different from new scrap, old scrap has experienced quality degradation and contamination and is much more difficult for materials recycling.

Much of the R&D work has been conducted on recycling the reinforcement, the matrix, or both, and various technologies, yet to be commercialised, have been developed. As far as the true material recycling is concerned, the re-enforcement fibre is the central focus, and the matrix (PMC) is recovered mostly as energy or secondary fuels. Generally speaking, there are three types of recycling methods: (1) mechanical recycling, (2) chemical recycling, and (3) thermal recycling. Mechanical recycling involves shredding and grinding followed by screening to separate fibre-rich and resin-rich fractions for reuse. It is very energy-intensive and the recyclates are of low quality. Chemical recycling involves either chemical depolymerisation of the matrix into oils or chemical removal of the matrix, both freeing up high value reinforcement fibres. However, this technique lacks flexibility and is hardly feasible for industrial applications at this moment. Thermal processing uses high temperatures (between 300 and 1000°C) to decompose the resin and separate the reinforcement fibres and fillers. Clean fibres or inorganic fillers are regenerated, and secondary fuel or thermal energy can be produced through pyrolysis, gasification or combustion. However, the quality of the recovered fibres or filler materials degrades to a varying extent during thermal processing.

A lack of markets, a high recycling cost, and the lower quality of the recyclates versus virgin materials are major commercialisation barriers. Environmental legislation will help promote recycling, but long-term technological developments are required. Developments are needed from three main areas:

- Material developers for new and easily recyclable composite materials
- Material recyclers for more efficient and intensified separation and purification technologies, and for improved quality of recyclates

- Production mechanisms that can use recycled composites and recycled fibres instead of using only new ones; change of feedstock

How to Progress

It is thought that by 2030, innovative research and development, new separation and recycling technologies for composite material recycling will be available and more easily recyclable composite materials will be developed for the industry. As another long-term vision, we could expect that a car could be built with 100% recycled materials and that it could also be 100% recyclable. A dream of a car created from waste could become true.

To reach these ambitions and goals, in particular the three critical development areas addressed above, extensive R&D efforts are needed for the development of improved recyclable composites and much more efficient separation technologies from physical, thermal and chemical perspectives. Inter-disciplinary knowledge is needed, and joint efforts from material design, material production, product design and recycling are indispensable. The following proposed topics cover three essential R&D challenges and are thought to be the key to success for the development of truly recyclable composite materials and their true recycling from all aspects: (1) recycling of composite materials and their constituents; (2) designing and engineering products for end-use properties including recyclability; and (3) maximising the product quality of each material use cycle.

The first research topic focuses on the development of new and more efficient separation technologies (physical, chemical and thermal) for the recycling and recovery of composite scrap (new and old). The research and development will concentrate on two important industrial application sectors, (1) automotive and (2) aerospace industries, where composite materials have already been widely used. The second research topic is devoted to composite design and manufacturing for reusability and recyclability. This area is obviously the least developed and will be an important task for the material developers and manufacturers in the future. New and groundbreaking technologies are needed for the future development to meet both the end-use properties and the recyclability. The third topic relates to the quality of the recycled materials. The quality degradation, in particular the reinforcement fibres, has been a common problem in different types of recycling technologies. The lack of practical markets for the recyclates hinders the commercialisation of composite recycling. This problem could be solved in both directions: (1) improving the quality of the recycled materials, and (2) increasing the tolerance of the manufacturing process with more recycled fibres and/or matrix.

Research Activities Needed, 2017 Deliverables and Disciplines Involved

Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. Separation and purification of fibres, metals, matrix materials with maximised materials and energy recovery	Five examples on the lab scale: glass/carbon fibres, Al alloys, thermosets; one demonstration set-up in automotive sector	Chemical and process engineering, thermodynamics and thermal processing, materials and metallurgical engineering, mechanical engineering
2. Linking the material recyclability to material and product design, proper balance between materials properties and recyclability	Proof of concepts in lab scale for two examples: aircraft and automotives	Process and product design, materials and metallurgical engineering, mechanical engineering, chemical and process engineering
3. Increasing the number of life cycles of the composite materials (>2), decreasing the rate of down-recycling	Two examples for demonstration, based on research topics 1 and 2.	System design, thermal processing, materials engineering, chemical and process engineering, market and management science

5 Process intensification and fuel cells using a multisource multiproduct approach

Background – Why This Milestone

The need for fundamental changes in energy generation to obtain a truly sustainable development is the driving force of the impressive worldwide research effort in fuel cell (FC) science and technology. Fuel cells (FCs) are electrochemical devices for the conversion of chemical energy into electricity, characterised by a high efficiency and a low environmental impact. Therefore, they are the ideal candidates for future energy-power conversion. However, the large-scale application of this technology is limited by factors such as electrolyte performance, catalysts activity, membrane electrode assembly durability and costs, together with problems related to the fuel production and storage. R&D efforts in various fields are devoted to the improvement of FC materials and to new technologies for fuel production from fossil fuels, biomass and water with hydrogen as an energy carrier for electricity production.

The implementation of the process intensification strategy characterised by a multidisciplinary approach to the fuel cell devices and the whole process will allow the current limitations to be overcome and improve performance in terms of efficiency, flexibility, productivity and overall sustainability.

Current State-of-the-Art

The main fields where fuel cell technology has wide applications are the following:

- Transportation
- Portable energy supplying devices
- Stationary power generation.

Different types of fuel cells characterised by various operative temperature ranges, fuels and electrolytes are used, depending on the application, power output and operating conditions. The Polymer Electrolyte Membrane (PEMFCs), owing to the low operating temperature and high power density, are ideal for mobile and small applications (such as energy sources for vehicles, cell phones, laptop computers). Despite the promising results obtained on the laboratory scale, most of the PEMs for FCs available today are far from able to meet the commercial durability targets for stationary and transportation applications (lifetimes longer than 5000 h and 40,000 h, respectively). Performance and durability of the Membrane Electrode Assembly (MEA) are often reduced by mechanical and chemical failures. During FC operation, membrane swelling and shrinking occurs with changing relative humidity and can induce fractures in the MEA. Moreover, radical species produced at the electrodes in the presence of cross-over phenomena can attack the polymer. Among the various perfluoro ionomers developed, Nafion membranes still dominate the PEMFC market today because of their high proton conductivity and relatively high chemical, thermal and mechanical stability. However, the main drawback of Nafion remains the high cost (600-1200 USD/m^2), which limits its practical applications. The electrodes currently used in MEAs are made of a thin catalytic layer composed of a high surface area carbon support, loaded with nano-scale catalytic particles of platinum mixed with ionomer recast dispersion. The high catalyst load implies a high cost, although the platinum and the whole polymer fuel cell can be recycled. Moreover, the use of platinum makes the fuel cell sensitive to CO presence in the hydrogen feed stream, which, as a consequence, needs strong purification prior to being fed to the PEMFC. Therefore, the real application of FCs is limited not only by the necessary improvements in materials constituting the PEMs and electrodes, but also by the auxiliary technology required for the fuel production, in particular when bio-fuels or biomass become the preferred primary energy source.

At present, global hydrogen production mainly relies on processes that extract hydrogen from fossil fuel feedstock, in which 96% of hydrogen is directly produced by fossil fuels, and the remaining 4% is produced by electricity generated by fossil fuels. Conventionally, the most important processes used for hydrogen production are based on steam reforming of hydrocarbons and coal gasification. These processes are performed in huge conventional plants where various reactors and separation units are required for achieving the desired H_2 purity level (CO<10 ppm) necessary for avoiding the poisoning of the catalysts in PEMFCs. The size of these plants is an important limitation of PEMFC use on a large scale; the miniaturisation of these plants appears quite complex and ineffective at the present time.

Although PEMFCs appear ideal for transport applications and portable devices, Direct Methanol Fuel cells are explored as an alternative, particularly for the latter. The Molten Carbonate Fuel Cells (MCFCs) and the Solid Oxide Fuel Cells (SOFCs) can be considered a suitable technology for stationary power generation. Direct Carbon Fuel Cells (DCFCs) are a promising type with a large thermodynamic head start, but this is still in the R&D phase. Early explorations and demos are in development for internal reforming fuel cells as hydrogen power co-production devices.

How to Progress

Intensified fuel cell based processes for transportation and portable devices sectors

To reach the current milestone, the research efforts in the next 20 years should focus on the development of new concepts that would integrate both material science and process engineering.
Some of the most promising strategies for developing advanced materials for the PEMFCs are:

- Hybrid functional materials in which more phases coexist to have a synergistic effect on ionic transport properties and stability, as well as reduced crossover
- Morphology control for better water channel formation and proton transport without excessive water swelling (e.g., block copolymer over random copolymer)
- High temperature PEM materials with functional groups and/or additives enabling proton conduction under non-humidified condition
- Electrodes with controlled architecture for interfaces and transport phenomena optimisation
- Cheap catalysts based on non-precious metals

The integration of membrane reactors (MRs) and membrane separation units in the H_2 production plants constitutes a good solution to the reduction of the reaction/separation/purification stages. MR technology allows a reduction in the size of the separation stage after the reactor to recover a pure hydrogen stream, also improving the yield of the process. This means lower energy consumption, lower footprint area occupied by the plant, enhanced exploitation of raw materials, and reduction of the total unit size and cost. The concepts of this intensified process of integrated membrane plants that, up to now, have been associated only with hydrogen production cycles from hydrocarbons, can be rapidly extended to plants for the conversion of biomass that constitutes an important renewable source for hydrogen production. An important result of the reduction in plant size is the possibility of building fuel processors on fuel cell vehicles based on PEMFC. Therefore, this option becomes more concrete and reliable.

Intensified fuel cell based processes for stationary power generation

Direct Carbon Fuel Cells (DCFCs), have large thermodynamic advantages over conventional fuel cells and heat engines. In particular, a high temperature DCFC that converts carbon into CO is a self-regulating system and efficiencies far beyond the Carnot limit can be obtained because heat is supplied to the system and is converted into electric power. Additionally, systems in which the carbon is internally gasified, before being electrochemically converted, offer several of these advantages. Internally reforming high-temperature fuel cells (IR-SOFC and IR-MCFC) can be operated as very flexible co-production systems. Operated in a conventional mode, mainly electric power and heat are produced, while in co-production mode, hydrogen, electric power and relatively little heat are produced. The inevitable heat losses are effectively used for the endothermic reforming reaction to achieve a high overall efficiency of up to 95%, in terms of hydrogen and the electric power produced. The small amount of waste heat is not counted in this efficiency definition, as is usually done for CHP systems. Compared to conventional operation in high-power mode, twice as much electric power can be produced by the same FC with a comparable amount of syngas (hydrogen/CO/CO_2/H_2O) also produced. System efficiency, in terms of hydrogen/CO and electric power, is then decreased from 95% in the high-efficiency mode to 75% in high-power mode. Integrated and flexible systems fed by natural gas/biogas producing electric power, syngas and heat are envisaged, and the first demonstrations can be realised today. However, more flexible and high-power units should be developed, to be used to compensate fluctuations in wind and solar electricity production. In this respect, the SOFC-HELP concept should be explored further and fuel cell and membrane R&D should co-develop and be closely intertwined. In the short term, an MC gasifier with an MCFC or SOFC is proposed to be an excellent combination for obtaining high efficiencies in the co-production of heat, power and syngas in distributed generation.

Coproduction of hydrogen and power is one way to reduce Nernst loss in high temperature fuel cells. The other way is the development of high temperature ceramic proton conducting electrolytes for PCCFC's. In PCCFC's, steam, the reaction product, is produced at the cathode side and is not diluting the fuel at the anode side.

Research Activities Needed, 2017 Deliverables and Disciplines Involved

Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. Integrated membrane systems for H_2 production from light hydrocarbons, carbon and biomass	Two to three concepts with proof of principle at lab scale	Chemical engineering; Reaction engineering; Process Engineering; Electrochemical engineering
2. Miniaturised membrane systems with PEMFC for energy production in transportation and portable devices	One to two concepts with proof of principle at lab scale. Reduction of the reaction stages of plant	Chemical engineering; Mechanical engineering; Process Engineering; Electronics; Electrochemical engineering
3. New perfluorinated and/or non-perfluorinated materials for PEMFC	Three to four proofs of principle at lab scale; Bench tests; Improvement of the lifetime and durability (>40000 h) under real conditions	Chemical engineering; Material science; Electronics; Electrochemical engineering
4. Direct Carbon fuel cells (DCFCs) for stationary applications	Two to three concepts with proof of principle at lab scale	Chemical engineering; Reaction engineering; Process Engineering; Electrochemical engineering; Mechanical engineering; Process Engineering
5. High-temperature proton conducting membranes and fuel cells (PCCFCs)	Identification of a number of high conductivity proton conducting ceramic membranes and a proof of principle at lab scale of a PCCFC	Materials science; Electrochemical engineering; Mechanical engineering; Process Engineering
6. SOFC-HELP concept (Hollow Electrode Loose Plate)	Proof of principle at lab scale of a SOFC-HELP	Materials science; Electrochemical engineering; Mechanical engineering; Process Engineering
7. Co-production of hydrogen and power by internal reforming high temperature fuel cells (MCFC and SOFC) from natural gas and biogas	Field demonstration of the concept	Reaction engineering; Process Engineering; Electrochemical engineering; Mechanical engineering

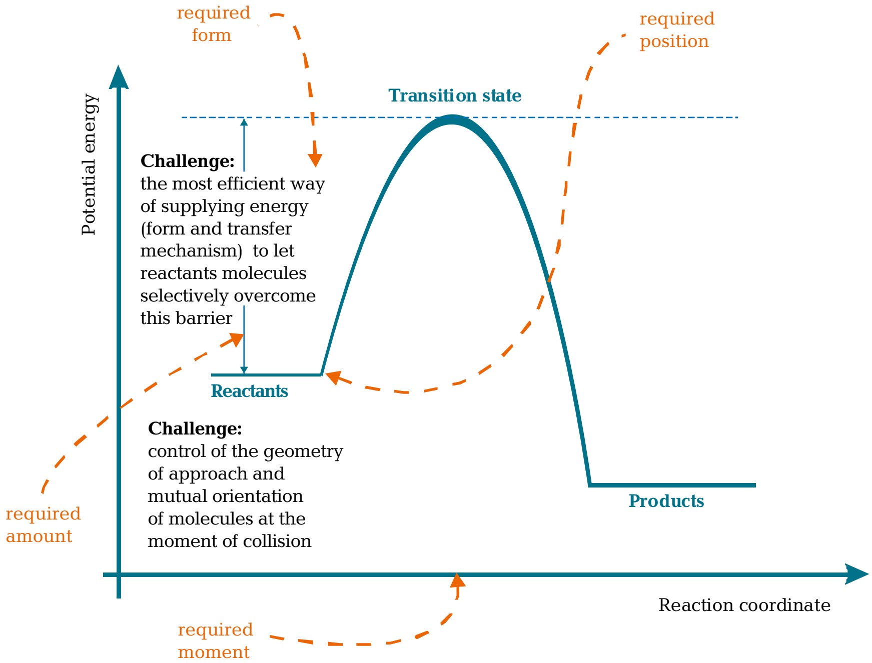
6 Towards perfect reactors: Gaining full control of chemical transformations at the molecular level

Background – Why This Milestone

The control of chemical reaction pathways at the molecular level presents undoubtedly the most important scientific challenge on the way to fully sustainable, thermodynamically-efficient chemical processes. The most obvious advantages of enhanced molecular reaction control are i) higher reaction rates leading to low-temperature processes and smaller equipment; ii) better selectivities leading to minimisation or elimination of waste; iii) reduced requirements for separation operations, which are responsible for ~40% of energy consumption in chemical and related industries; and iv) the possibility for tailored manufacturing of new, advanced products.

It is clear that to meet the future needs of the sustainable world, a new generation of chemical reactors ("Perfect Reactors") must emerge. A groundbreaking solution in those reactors will consist of creating a reaction environment, in which the geometry of molecular collisions is controlled, while energy is transferred selectively from the source to the required molecules in the required form, in the required amount, at the required moment, and at the required position (Figure 7).

Figure 7: Schematic representation of basic challenges in controlling chemical reactions.



Current State-of-the-Art

In the current practice of chemical reactors, to increase the number of molecules at energy levels exceeding the activation energy threshold, conventionally conductive heating is applied. However, conductive heating offers only a macroscopic control upon the process and is thermodynamically inefficient. It is non-selective in nature, which means that non-reacting (bulk) molecules heat up together with the reacting ones. Additionally, other elements of the reactor (e.g., catalyst support) are unnecessarily heated. Also, the conductive heating generates temperature gradients, creating a broad distribution of molecular energy levels. This results in ineffective collisions by the molecules with too low of an energy (waste of energy) and in generation of unwanted by-products by the molecules that have enough energy to enter the side-reactions (waste of material).

In some processes, molecular orientation can be controlled by immobilising the molecules for the duration of the reaction in confined nano-spaces by imposing “hard walls” on structures (e.g., shape-selective catalysts or other molecules (e.g., cyclodextrins). Thus, the reacting molecules are forced to either assume a certain position inside the offered structure or not to react. Alternatively, fundamental work in the field of chemical physics provides spectacular examples of controlling molecular alignment, orientation and activation using spatially oriented external fields, such as electric field or laser beam. For instance, selective breaking of chemical bonds is possible using laser light of the correct frequency. Rate increases by factors greater than 100 are reported, without an increase in process temperature. In heterogeneous catalysis, the nano-particles of noble metal catalyst can be selectively heated up by the use of a microwave field.

How to Progress

To reach the current milestone, the research efforts in the next 20 years should focus on the development of new engineering concepts of “Perfect Reactors”, which would integrate several functional steps as shown in Figure 8. This should be done by simultaneously addressing four Process Intensification domains: spatial (structured reactors and surfaces), thermodynamic (alternative forms of energy), functional (combinations of energies and materials, in-situ separations) and temporal (dynamic/pulsed energy supply, ultra short-time contacting).

Figure 8: Schematic representation of functional steps integrated in a “Perfect Reactor”.

1. (Pre)separation and removal of molecules not needed in the reaction
2. Equalization of molecular trajectories and velocities, minimization of random motions
3. Control of spatial orientation of molecules and geometry of collisions
4. Selective energy transfer to the required molecules in the required form, in the required amount, at the required moment and at the required position
5. Selective and instantaneous product removal or immobilization
6. Uniform removal of energy generated in the reaction, efficient reaction quench

The integration of all four domains and the corresponding PI-concepts presents an essential prerequisite of the success of the milestone, and this is where the research should focus in the coming years. Additionally, the research should focus on engineering-enhanced control of molecular alignment, orientation and activation in spatially structured reactors using electric, magnetic or electromagnetic fields, or combinations thereof. It should include investigations of the targeted introduction and control of laser, light or microwave fields, for example, in the confined, well-defined geometries of milli- to nano- (or in some cases even pico-) channel reactors and using materials with different energy-absorbing properties in the reactor design for local creation of the desired thermal conditions. A combination of the above with the in-situ separation techniques could form the subsequent research steps. The exploration of molecular control in systems involving condensed phases should further be extended. In all interdisciplinary research activities, bridging chemical engineering, chemical physics, catalysis, material science, electronics and advanced computer modelling will be absolutely essential.

Research Activities Needed, 2017 Deliverables and Disciplines Involved

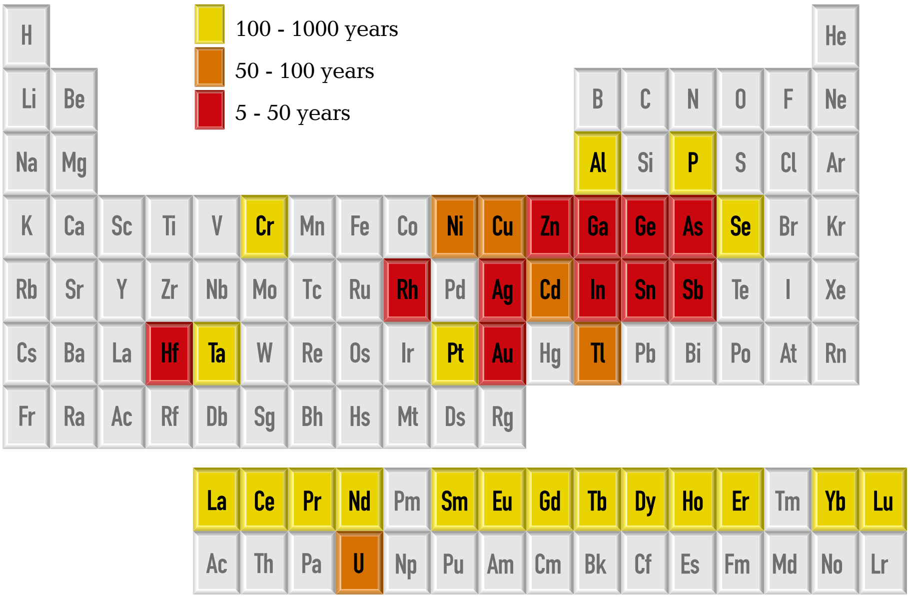
Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. Targeted (dynamic) introduction of electric, magnetic and electromagnetic fields in spatially structured reactors for molecular alignment, orientation and activation	Two to three concepts developed with proof-of-principle on laboratory scale	Chemical physics, materials engineering, electronics, chemical engineering, chemistry, catalysis, advanced computer modelling
2. Manipulation and control of local thermal conditions in reactors, by choice of materials or by acting on media	Two to three concepts developed with proof-of-principle on laboratory scale	Materials engineering, physics, chemical engineering, catalysis, advanced computer modelling
3. In situ molecular separations in spatially structured reactors	One to two concepts developed with proof-of-principle on laboratory scale	Materials engineering, physical chemistry, chemical engineering
4. Molecular alignment, orientation and activation in reactions involving condensed phases	One to two concepts developed and demonstrated on a molecular scale	Physics, chemical physics, chemical engineering, advanced computer modelling
5. Instrumentation to observe, measure and control on time and space scales of molecular events	Right methods & instrumentation for local measurements identified; two to three diagnostic methods translated to lab scale	Physics, signal processing, chemical engineering, process engineering, instrumentation and analytical sciences

7 Elemental sustainability: Towards the total recovery of scarce elements

Background – Why This Milestone

Some modern so-called low-carbon technologies are actually broadening concerns over future elemental sustainability for a wide range of elements (Figure 9). To address rapidly depleting metal sources, such as indium and silver, we need to be more innovative in recovery technologies that essentially turn waste into a resource. A multi-disciplinary blend of chemistry, engineering and biotechnology is required to realise this ambition.

Figure 9: Number of years remaining of rare and precious metals if consumption and disposal continues at present rate.



Current State-of-the-Art

Recycling and recovery of metals from waste and end-of-life products is not new, and this is already playing an important role in the steel and base-metal industries. Currently, nearly 45% of steel is produced from steel scrap, and more than 30% aluminium is produced from recycled metal. Furthermore, approximately 30% of zinc, 40% of copper and 50% of lead supplied to the market are currently produced from their secondary resources. Among these, steel recycling is exclusively conducted during primary steelmaking using BOF (Basic Oxygen Furnace) or EAF (Electric Arc Furnace) steelmaking processes. For non-ferrous metals, they are mostly recovered separately in secondary smelters processing only scrap metals or industrial waste-bearing non-ferrous metals. However, this does not mean that these metals are recovered to their maximal extent. Instead, there is still potential to increase the recycling and recovery rate of these metals. For example, municipal solid waste and landfill sites contain significant amounts of steel and base metals such as copper and aluminium. Physical recovery using magnetic separation and eddy current separation can regain approximately 60% of the metals from waste combustion/incineration bottom ashes, but the rest of the metal in the bottom ash and fly ash are lost. New and more efficient physical and metallurgical recovery technologies are needed in the future.

In contrast, the recovery of scarce and precious metals is much more difficult due to their very low concentrations and dispersion in a wide range of waste streams. The current industrial practice is to capture these precious metals with bulk production of heavy metals such as copper and lead. Smelting of copper and lead concentrates together with gold/silver concentrates, or mixed with pre-sorted e-wastes, can bring precious and PG metals into the copper and lead stream. At the end of the refining step of copper or lead through electro-refining, the precious and PG metals are present in the anode slime. The anode slime becomes a much richer raw material for precious metals recovery through leaching and electrowinning process, sometimes in combination with roasting, which is a high-temperature pyrometallurgical conversion process.

To recover precious metals (gold, silver and PGMs) from secondary resources, the concentration process is always the first step. This process is conducted either through a pyrometallurgical smelting process or a hydrometallurgical (selective) leaching process. For various types of waste materials, mechanical treatment might be applied, such as thermal expansion to remove a gold coating. To concentrate precious metals in solutions, ion exchange and adsorption are broadly used in precious metals recovery.

Compared to precious metals and PGMs, rare and rare-earth metals are even scarcer in the EOL products and wastes. Rare-earth metals are not currently recycled but are gaining attention around the world for recycling due to the very localised natural resource and production (China) and their critical importance in high-tech products. Efficient collection, separation and recovery technologies are not yet available, and some initial efforts are being made. Examples include recycling of rare-earth magnet powder from hard disc drives (HHD) through selective crushing, hydrometallurgical separation, and recovery of neodymium and dysprosium. However, this technology is at a very preliminary research stage. Currently, society is heavily dependent on the supply of REE produced from primary mine resources in China.

How to Progress

By combining different alternative sources of rare and precious metals (municipal waste, aqueous wastewaters, electronic goods, low-grade ore and soils) with novel and benign technologies, we could reach our vision of complete closed loop cycling of all elements by 2030. We can revolutionise our interaction with the fundamental elements of nature, switching from dispersing elements throughout our environment to concentrating them in synthetic ores for useful applications.

For instance, an ideal future scenario for Waste Electronic and Electric Equipment (WEEE) could combine bioleaching and biosorption of WEEE to selectively recover all elements without the need for toxic reagents or energy-intensive processes. Very little work has focused on the biosorption of precious metals from WEEE leachate. Further research is vital to fully realise the potential of bioleaching and biosorption for metal recovery from WEEE both individually and in combination. Even more important for the future is the design of new EEE prior to manufacture, to integrate methods for the easy separation and recovery of valuable components at their end of life. The use of smart materials and designed active disassembly would greatly facilitate either the direct reuse of high-value components or the recycling of scarce elements into new materials. Directed research into developing so-called 'smart materials' and technologies should lead to a greater recovery of elements and reductions in the use of incinerators and landfills in the future.

Another example of how benign techniques could be combined to create a complete and sustainable recovery of elements is in an urban mine or landfill. A process could potentially consist of bioleaching, biosorption and phytoextraction in a typical urban landfill to recover the valuable elements contained within it. Following technologies for final metal extraction should be applied after biosorption or hyperaccumulation:

- Separation and concentration: solvent extraction, ion-exchange, membrane technology, supercritical fluid treatment, precipitation and crystallisation
- Metal extraction and precipitation: electrowinning and/or electrorefining, cementation, gas reduction

Innovation in initial metal extraction from waste streams, together with the integration of processes to available metallurgical unit operations, will lead to new processing flowsheets and technology tailored to each individual waste stream for different targeted metals. Minimisation of new waste generation is critically important. New socio-techno-economic challenges in the total recycling process will drive the future R&D efforts in the development of these new and abundant secondary resources. This by no means covers all possible solutions to the problem of elemental sustainability; other lateral and innovative methods and technologies are needed that provide groundbreaking solutions to our scarce element dilemma.

Research Activities Needed, 2017 Deliverables and Disciplines Involved

Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. Plant hyperaccumulators	Two to three plant species, either bred or transgenic, that show hyperaccumulation of rare and precious metals	Chemistry, Biology, Agronomy
2. Smart design	Proof of separation by design of smart and biomaterials for recovery of rare and precious elements in WEEE	Materials science, Engineering
3. Biosorption	Two to three new bioderived materials that show economic levels of selective absorption of scarce elements.	Chemistry
4. Urban mines – metal recovery from MSW (incineration or landfill)	Proof of principle of recovery of elements from municipal solid waste either directly, from incineration ashes, waste waters or landfill sites	Chemistry, Engineering
5. Scarce and precious metal flows	Advanced knowledge of element flows through materials and waste	Environmental science

8 Production systems for personalised medicine

Background – Why This Milestone

Personalised medicine represents a major paradigm change for the healthcare industry. Therapy in conventional medicine is based on the assumption that a drug applied properly can serve all patients. Therapy in personalised medicine is based on phenotype, genotype and other features of an individual patient or patient collective. It is clear that to meet the future needs of Personalised medicine a new production system must emerge:

- Drugs tailor-made for patient sub groups / individuals therefore drug design could become part of the manufacturing process
- More small-quantity drugs (instead of blockbuster drugs)
- More slightly modified drug varieties for personalisation
- Various drug delivery/packaging systems (adjusted doses)

- Very flexible, small-volume production
- Intensified, integrated, dedicated, efficient unit operations in modular, standardised equipment assemblies and highly automated, flexible assembly-lines

Current State-of-the-Art

Currently, drugs are mainly produced in multi-purpose/multi-product facilities in a batch operation. Overall processing time can reach up to more than 100 days, requiring a complex global supply chain. This process is no longer economical, even for conventional drugs, and is prohibitive for small volume, tailor-made personalised medicine drugs.

A new production paradigm will be required for personalised medicine drugs that combine process intensification concepts, novel technologies and a new operation mode. Industry-type manufacturing will be replaced by assembly-line-type factories that are fully automated and dedicated to a particular drug. The drug design process will become an integral part of the manufacturing process.

How to Progress

To establish an efficient production system meeting the requirements of personalised medicine, various technologies need to be developed and/or adapted to the task at hand:

Biological Entities (e.g., antibodies, therapeutic proteins, vaccines):
- Automation of cloning, expression and selection (first examples for cloning and expression (NHL), selection platforms described for scFv (e.g., Morphosys))
- Automated and parallel GMP-production of small quantities (Upstream: e.g., microorganisms, plants; Downstream: extraction, purification, formulation)
- Process control

Chemical Entities:
- Technologies in drug development and manufacturing are increasingly identical because quantities are very similar for personalised products
- Miniaturisation, parallelisation and automation of manufacturing processes are key technologies
- Intensification and Integration of process unit operations are indispensable for manufacturing
- Biological systems will dominate novel drugs for personalised medicine
- Drug delivery systems will become more important to allow for patient-specific therapeutic strategies

Research Activities Needed, 2017 Deliverables and Disciplines Involved

Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. Establish modular platform of continuous, parallel and disposable processing units for biological drugs (e.g., cloning, expression and selection units, fermentations/cell retention, down-stream processing with chromatography)	Select and adapt existing processing units to particular requirements, develop novel prototype units for main processing steps and demonstrate basic concepts at least on the laboratory scale	Medicine, Microbiology, Biotechnology, Biochemistry, Chemical Engineering and Automation Technology
2. Establish modular platform of continuous, parallel and assembly-line processing units for chemical drugs(e.g., chemical reaction and separation and formulation)	Select and/or adapt tailor-made modules for reaction, separation and formulation, develop novel prototype units and demonstrate basic concepts, at least on the laboratory scale	Chemistry, Computer Science, Physics, Chemical Engineering, Catalysis,
3. Adapt and/or develop modular, standardised and automated robots, including on-line analysers and logistics	Demonstrate new assembly-line manufacturing with advanced on-line sensors and logistics for selected drugs	Operational Research, Sensor Technology, Systems Engineering, Process Control

9 Bio-hybrid organs and tissues for patient therapy

Background – Why This Milestone

There are medical needs that must be addressed by regenerative technologies, including heart failure, diabetes, liver failure, osteoporosis, Alzheimer and Parkinson diseases, severe burns, and spinal cord and nerve injuries. New therapeutic areas, particularly the development of neo-organs with complex three-dimensional structures, may offer new solutions to tissue loss or organ failure. To date, many tissues have been developed in the laboratory and laboratory-grown organs are beginning to take shape. Nevertheless, many obstacles and challenges remain. A major limitation is related to the transport of oxygen and nutrients to neo-tissues, both in vitro and in vivo, and to the neovascularisation of the living tissue. The biofabrication of an organ or tissue requires a biomimetic approach that utilises expandable cells, a cell-affinity biomaterial that serves as scaffold and an optimal bioreactor. Biomaterial scaffolds may provide the biochemical, physical and mechanical cues to direct stem cells and to stimulate the self-organisation of tissues. Among biomaterials, polymeric membranes are attractive due to their highly selective permeability, micro- and nano-structured properties and biocompatible characteristics. Bioreactor technologies are key enabling technologies for individualised automation and mass production. The bioreactor, through fluid dynamics modulation, may simulate the complex in vivo physiological environment, ensuring an adequate mass transfer of nutrients and metabolites and the molecular and mechanical regulatory signals. The creation of a biomimetic environment requires the use of biomaterials, such as membranes, with specific physico-chemical, morphological and transport properties on the basis of the targeted tissue or organ. This technology must be able to provide the cells with the same regulatory factors and biophysical, mechanical and chemical stimuli to direct the differentiation of cells into a specific phenotype. The use of stem cells opens the possibility of creating in vitro tissues or organs and establishing a therapy based on a platform technology using innate mechanisms of repair of tissue engineering with clinical significant success.

Current State-of-the-Art

The growing crisis in organ transplantation and the aging population have driven a search for new and alternative therapies. There are currently 108,034 patients on the United States transplant waiting list. Despite a growing number of donors, the availability of suitable organs is still insufficient. Cell transplantation is primarily useful for replacing small areas of tissue. Bioartificial homologues are necessary to replace larger tissue areas or entire organs. Small parts of bioartificial tissues have been successfully developed experimentally in animals for blood vessels, bladders, bones, tracheas and intestines. To date, the engineering of complete organs and tissues is limited because of the difficulty in providing vascularisation and extracellular matrix signals.

In the past decade, many research efforts have been focused on the development of biomaterials to support cells and the growth of tissue. Improvements in the biomaterials that have been developed in these years are limited, in part because they represent a compromise. Living tissues can respond to changing physiological loads or biochemical stimuli, but synthetic materials cannot, which reduces their lifetime and represents a limit of the current medical paradigm that emphasises replacement of tissue. Cells are inherently sensitive to physical, biochemical and chemical stimuli from their surroundings. In vivo, the local cell environment or "niche" provides specific environmental cues that determine cell-specific recruitment, migration, proliferation, differentiation and the production of the numerous proteins needed for hierarchical tissue organisation.

Considering the increasing clinical and social needs, particularly for the age-related pathologies, it is time to consider a shift towards a more biologically and rationally based method for the development of new approaches that combine smart biomaterials with advanced cell therapy. Aging constitutes the collective early stages of all age-related diseases, so it is responsible for two-thirds of all deaths worldwide and 90% of deaths in the industrialised world. Tissue engineering using advanced biohybrid materials has the capacity to play a vital role in the anti-aging medical arsenal in years to come.

How to Progress

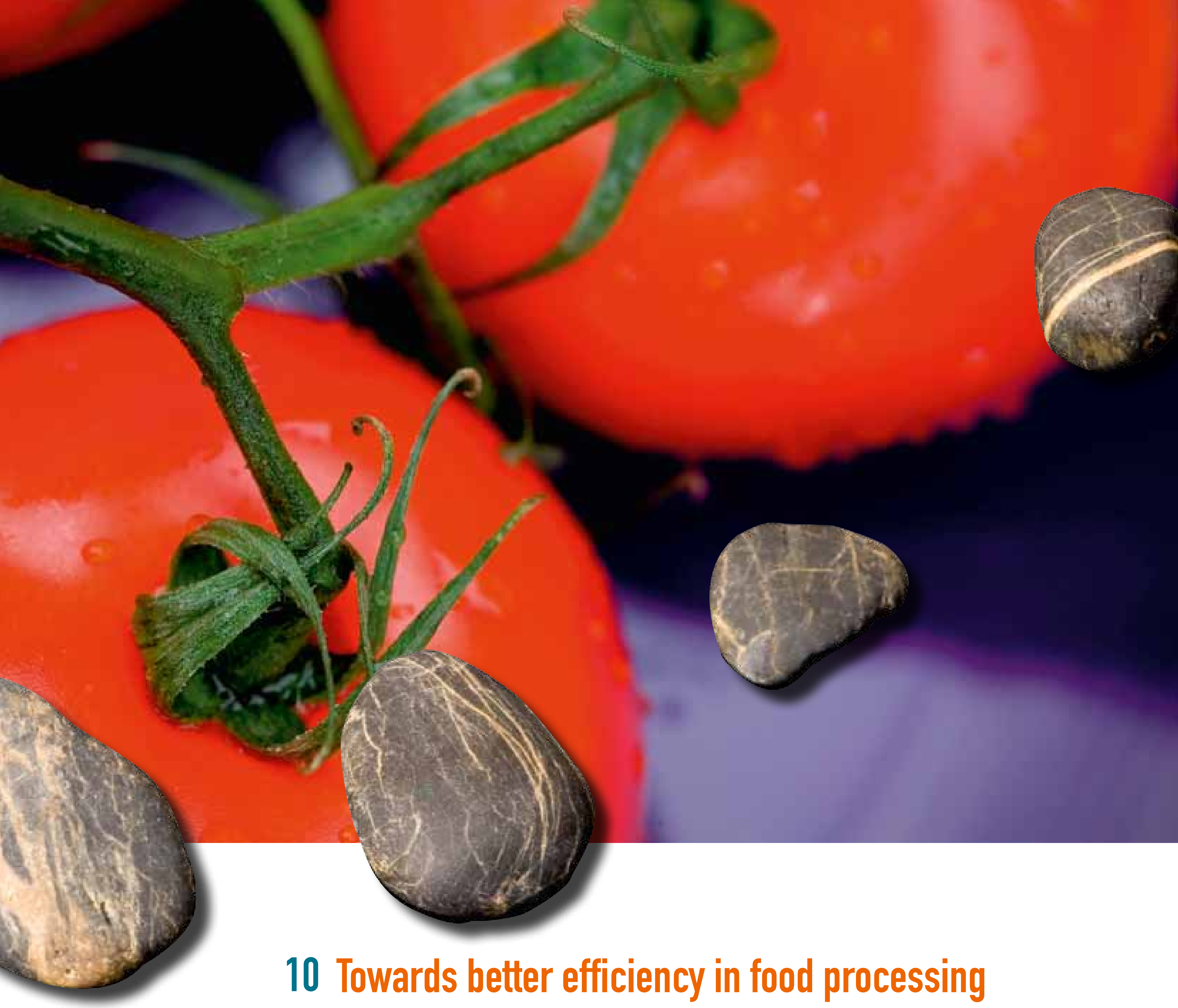
To reach the current milestone, the research efforts in the next 20 years should focus on the following:
- Development of biomaterials as instructive extracellular matrix for the differentiation of stem cells towards the formation of a new organ or tissue
- Engineering of a tailor-made regenerative biohybrid system
- Advanced biohybrid organs towards the goal of tissue regeneration (liver, pancreas, kidney, cardiovascular system, bone, cartilage, spinal cord injury, neuronal trauma, brain trauma)
- Integrated multifunctional biohybrid organs
- Production technologies for autologous implants
- Strategies for self-regeneration and self-repairing of organs and tissues
- Micro-organs and micro-tissues for testing new drug therapies
- Treatment of age-related diseases

The research strategies should focus on the implantation of bioartificial tissues and the induction of regeneration. These strategies seek to reconstruct damaged organs tissues with cell transplants or bioartificial tissues or by inducing resident cells to reconstruct them in situ. The goal is to develop tissue and organ homologues from stem cells and biomaterials that mimic extracellular matrix in vivo, providing not only the geometry and physico-chemical properties to maximise the migration, adhesion and proliferation of cells but also the capability to sequester and release biological signals essential for cell molecules. Biomaterial scaffolds, for instance semipermeable membranes, with a well-defined micro- and nano-structure are capable of restoring, replacing and/or enhancing tissue function, as well as stimulating the self-regeneration and self-repairing of organs and tissues.

Furthermore, the future research should be focused on the bioengineering of integrated multifunctional biohybrid organs and tissues that are able to perform in vivo functions that are influenced by molecules and signals from other organs, which are essential for the maintenance of body homeostasis.

Research Activities Needed, 2017 Deliverables and Involved Disciplines

Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. Advanced biohybrid organs towards the goal of tissue regeneration	Strategies for the reconstruction of damaged organs or tissues using stem cells by cell transplants or bioartificial tissues or by inducing resident cells to reconstruct them in situ	Medicine; biology; chemistry; chemical engineering; material science
2. Integrated multifunctional biohybrid organs	Three to five concepts of integrated multifunctional biohybrid organs including design and engineering methods of tailor-made integrated biohybrid organs	Medicine; biology; chemical engineering; material science
3. Development of new biomaterials.	Three to five new concepts of biomaterials (membranes, scaffolds) as instructive extracellular matrices for the differentiation of stem cells towards the formation of a new organ or tissue. Proof of principle at the laboratory scale	Medicine; biology; chemical engineering; chemistry; material science
4. Rejuvenation biotechnology	New strategies based on smart biomaterials with advanced stem cell therapies for the treatment of aging-related disease	Medicine; biology; chemical engineering material science

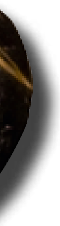


10 Towards better efficiency in food processing

Background – Why This Milestone

In recent years, the sustainability of our use of natural resources has become a major societal issue, due to increases in prices of food and fossil commodities. The underlying long-term causes are the steady increase of the global population; the strong growth in affluence and industrialisation in many regions of the world, leading to a much larger demand for more resource-intensive foods (such as meat) and the simultaneous degradation of land quality around the world, due to intensive use, increasing the effects of droughts and erosion; and the lack of abundant fossil resources, which drives the use of agricultural crops for non-food purposes.

This has made it clear that our food production should become more efficient, in the sense that less energy and water should be used and that more food should be obtained from the same amount of harvested crop. A careful analysis shows that this efficiency is possible: current food processing uses large amounts of water and, hence, uses a large amount of energy to dehydrate, while the overall



yield of food product from the original harvested crop is often less than 10% (dry weight basis).

In addition to more efficient primary production, the conversion of crop into food should be made much more efficient. One should bear in mind that the process of transporting food from the farm to the fork is long: preliminary processing at the farm, transportation, primary processing into ingredients or products, transportation, secondary processing into ready-to-use products, transportation, warehousing, transportation, retail, transportation, storage, preparation at home, and consumption. Each step should be considered to avoid local optimisation. For example, preliminary processing on the farm can avoid losses; preservation would allow steady transportation and processing would render the next steps in the chain much more efficient. The primary processing from a crop into an ingredient is usually highly optimised for the production of a single ingredient, while the remainder of the crop is usually collected and used as cattle feed, or even discarded. Although this feed is ultimately transformed into food via consumption by the cattle, this is performed with very low efficiency (typically 10 – 30 %, the rest being lost or converted into chemical or even toxic waste). Transition towards processing with a multi-product objective, for example by milder processing, would allow the direct use of more of the crops for human food, while more concentrated processing would reduce the amount of water used, reduce the fraction of raw material ending up in waste water, and greatly reduce the energy consumption (in the food industry, approximately 90% of all energy is used in some way for dehydration). At the end of the chain, much of our food is discarded (approximately 30% in Europe approximately 50% in the US), due to expiration (passing the 'best before' date), the product going unpurchased in the store, or disuse by the consumer and subsequent spoilage or disposal. In addition, home preparation accounts for a major part of the total energy use due to the use of natural gas or electricity for heating.

In addition to making the existing chains more efficient, there is a second challenge: the partial replacement of existing chains with inherently much more sustainable ones. An example is the development of non-animal protein products. This fast-growing market is hampered by lagging technology. Current technology to efficiently concentrate proteins from plants is very water-, chemical- and energy-intensive, just as is current technology for assembling these proteins into consumable foods. Finding efficient new processes for these two steps, and thereby replacing part of the meat supply chain by plant based protein products, would contribute greatly to producing larger amounts of food for more people with the same amount of agricultural land, reduce greenhouse gas emissions, and would contribute to better animal welfare (since current intensive cattle farms generally have relatively poor animal welfare).

In summary, the following developments are expected in the on the mid-term period:

- Processing using much less water, energy and waste

- Mild, multi-product processes that maintain the native functionality of all components (from current waste to future products)
- Better, milder preservation techniques, allowing the perception of 'fresh' while reducing the amount of food that has to be discarded (less waste)
- Efficient ways for fractionation of crops into (a.o.) functional protein fractions. This includes crops that are now investigated for use as non-food crops, and food and non-food biorefining
- Efficient and effective ways to assemble plant proteins into delicious and health foods (partially replacing meat with more sustainable alternatives).

Current State-of-the-Art

Currently, food is processed using large amounts of water. Typical processes run at 1 – 30 wt% solids, solely because this allows the use of traditional mechanisms of settling, centrifuging and filtering. However, sometimes a significant amount of the raw material ends up in the waste water; the residual water must be evaporated, which requires large amounts of energy. This is true not only for separation/refining (meat production; production of glucose or starch from corn, potato or wheat; refining of corn; separation of proteins from milk), but also for reaction processes (protein isolation, enzymatic hydrolysis processes, enzymatic synthesis or isomerisation processes, fermentation into bioethanol or other compounds) and structuring processes (e.g., Kweldam process, cheese production). There is no fundamental constraint in carrying out these conversions under much higher concentrations, or even without water. Separation or reaction under these conditions, however, does require deeper insight into the properties of the raw materials and the individual fractions. This area is where current knowledge is lacking.

The most common technique to open cells and disclose their components is to use heat (e.g., diffusion in refining sugar beets and canes) and often chemicals (e.g., in corn processing or in the production of many protein and carbohydrate fractions). This degrades and denatures the other components, rendering them suitable only for low-value applications. At the same time, the degradation products diffuse into the product juice, which then has to be treated extensively, using a large amount of chemicals and energy. Milder methods such as PEF treatment are now being discovered, which allows more a selective release, and therefore makes a large part of the conventional refining process redundant (e.g., the total purification train in sugar refining), and allows recovery of proteins, antioxidants and other components in their native state. Fractionation in the dry state is the ultimate solution; this has been shown for a few crops (corn, peas) and should be developed further for other crops. No chemicals are needed, and no water needs to be removed.
It is clear that these methods should be applicable to traditional crops and to new crops that are now mainly not considered for food use, such as algae.

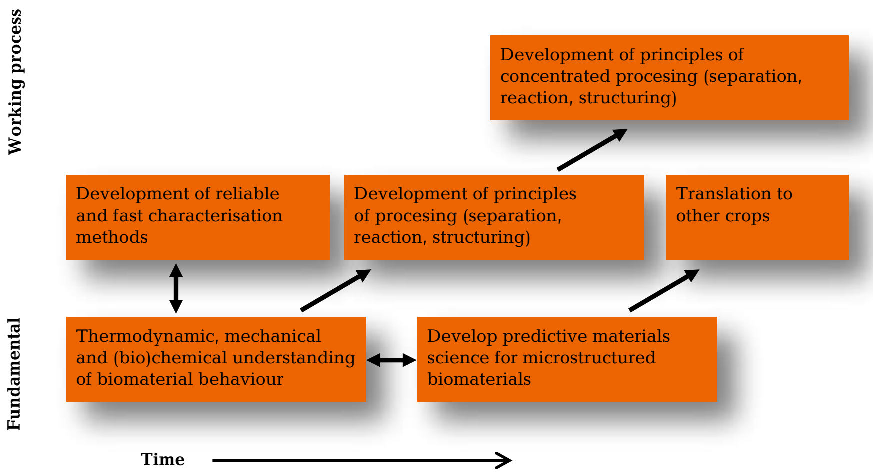
Isolating food-grade protein from algae may yield a new food source.

However, production of raw ingredients is not enough: much of taste is determined by the microstructure of a product. Current techniques to assemble products are rough, allowing only structuring down to the level of several micrometres, and even then, the structuring is not very precise. The use of unidirectional shear flow in mildly interacting colloidal suspensions has been shown to give a much better control over the internal microstructure, down to the 100-nanometre level. This combination of position and self-assembly (‘directed self assembly’) is seen as a promising route forward. Translation of nanotechnological assembly techniques to larger scales may be the following step.

How to Progress

It is important to obtain more insight into the properties of the materials to be separated. This will enable us to process these materials in concentrated form. A first step is the behaviours of dry raw materials (0 – 20 wt% moisture). If they are known, they can be used to segregate these components (e.g., shattering a kernel between the glass transitions of starch and gluten will separate these components). Especially in this regime, the behaviour of each raw material will be different, and should be studied. A general framework for approach and effective characterisation methods and systems are therefore important: for example, it has recently become possible to quantitatively understand the complete state diagram of many foods through solid-state thermodynamics. Thus, measuring the thermodynamic parameters will determine a large part of the system behaviour. However, additional insight should be generated on the properties and behaviour of the specific structure aspects (e.g., cell walls, intracellular structure) and the role they play during processing.

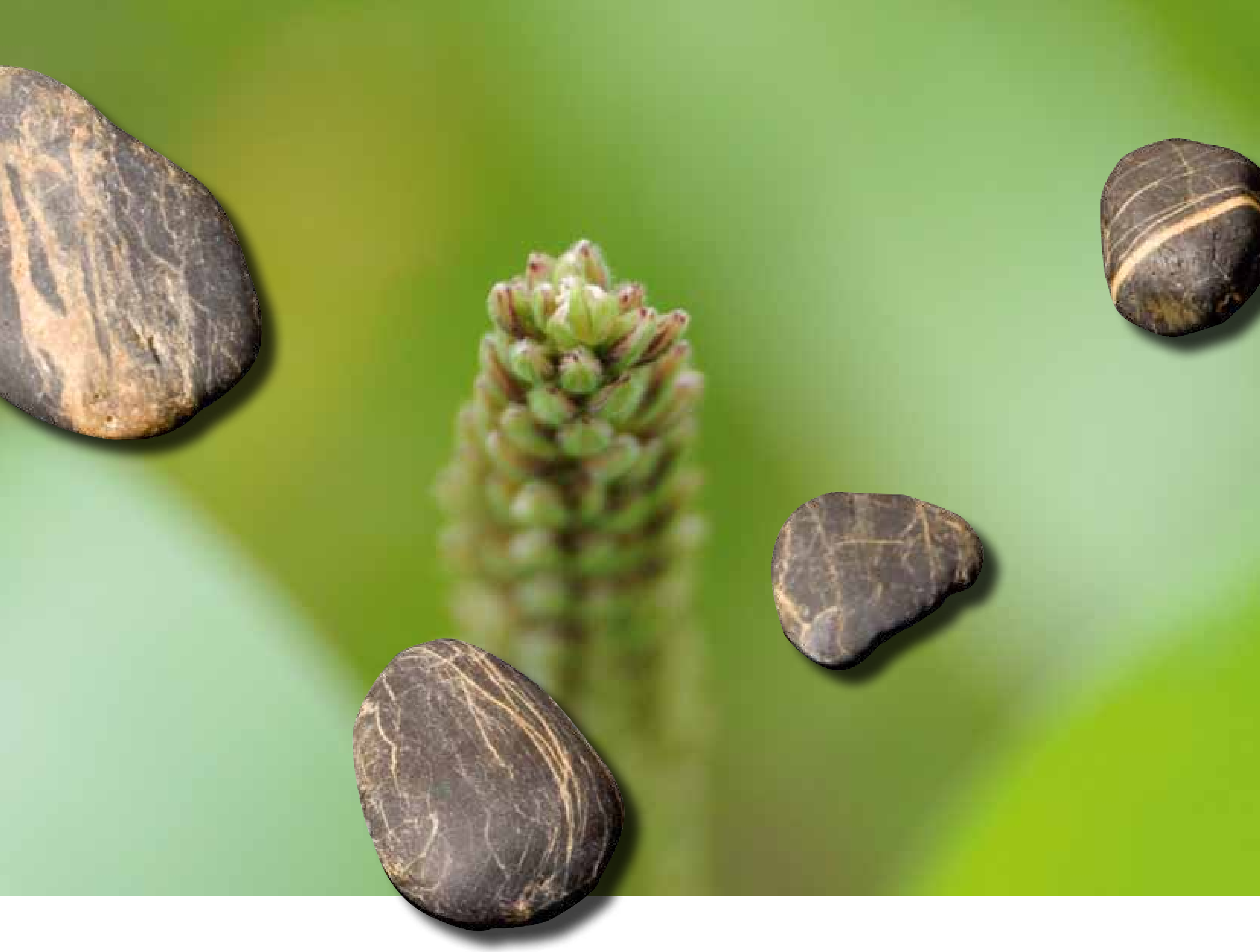
Figure 10: Schematic research progression.



A second regime is the behaviour of concentrated systems (20 – 60 wt% moisture). Utilising the specific interactions between colloidal or larger aggregates yields new mechanisms for separation and for product structuring. Here, the characterising parameters are on a colloidal scale: for example, attraction/repulsion, flow and deformation, hydrodynamic diffusion and segregation, and orthokinetic aggregation and stabilisation.
Based on insight into these regimes, new processes have to be developed, first on the lab scale, then a translation to continuous processing, and finally translation to larger production scales (pilot and up).

Research Activities Needed, 2017 Deliverables and Disciplines Involved

Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. System analysis for optimum production of food	A validated an integrated approach for system analysis, process design and optimisation for food production	Thermodynamics, food science and technology; operational design; chemical engineering; system analysis
2. Concentration and dry separation for better quality, less water and less energy use	1 – 2 selected concepts developed on pilot scale	Chemical engineering biology, biochemistry; food science & technology
3. Energy efficient dehydration of agricultural feedstock	Established concept, proof of principle	Chemical engineering, biology, biochemistry, food science and technology
4. Synergies between food, fuel, chemicals and materials	Integrated strategy developed for co-producing food, chemicals, fuels and engaging all parties involved	Chemical engineering, biology, biochemistry, food science and technology
5. Protein foods from bio-refining crops	Separation & product structuring processes established on pilot scale.	Chemical engineering, biology, biochemistry, food science and technology



11 Chemicals from biomass – integrated solution for chemistry and processing

Background – Why This Milestone

For a sustainable world, an increased role of biomass is very attractive, if not necessary. The main use of biomass is in food and feed, but biomass should be used also in other large applications, in particular as feedstock for the production of chemicals. Undoubtedly, the development of new resources for the chemical industry will lead to new products, such as polymers that will replace existing polymers because of better properties and/ or lower costs.

At the present, the chemical industry produces approximately 1750 Mtonnes of chemicals worldwide, of which approximately 300 Mtonnes are bulk chemicals, such as plastics, nylons, polyesters, and 1100 Mtonnes are base chemicals such as ethylene, propylene, but also sulphuric acid, lime, oxygen, hydrogen, chlorine, and ammonia. We expect that in the year 2030, a considerable quantity of bulk chemicals, at least 25% by weight, will be produced from biomass. A relevant question is how to build a process infrastructure suited to process the large variety of biomass feedstocks. In our view, the biomass will be processed in biorefineries that may be regarded as analogues to oil refineries. In this respect, it is useful to divide the feedstocks into two types: biomass produced as special crops and residual streams from food production and various other agricultural uses such as garden waste.

The first type of biomass involves the production of plants and algae with maximal target fractions, in particular carbohydrates, proteins, organic acids and lipids. The second type of biomass has a mixed and variable composition. Whereas in the first type, the challenge will be to separate valuable components in an economic way compared to traditional separation technology used for food application. In the second case, the yields after separation will generally be lower, and a large part can be processed into simple molecules by a robust technology. This processing can be performed by anaerobic digestion for dilute streams (30-70° C), to produce CH_4/CO_2, or conversion to syngas (> 500° C, produces CO/H_2), a technology under development for high dry-weight resources.

The valuable components deserve the development of dedicated processes. To fulfil our target to manufacture chemicals from biomass with the lowest raw material inputs, even when they are renewable, we should exploit the presence of molecular structures that are produced in nature as much as possible and, in doing so, significantly reduce the need for process energy and equipment. The more we will be able to recover molecular structures from biomass that currently are synthesised from naphtha fractions, the less chemical conversion steps will be required to produce the desired chemical building blocks, reducing the capital costs and energy inputs.

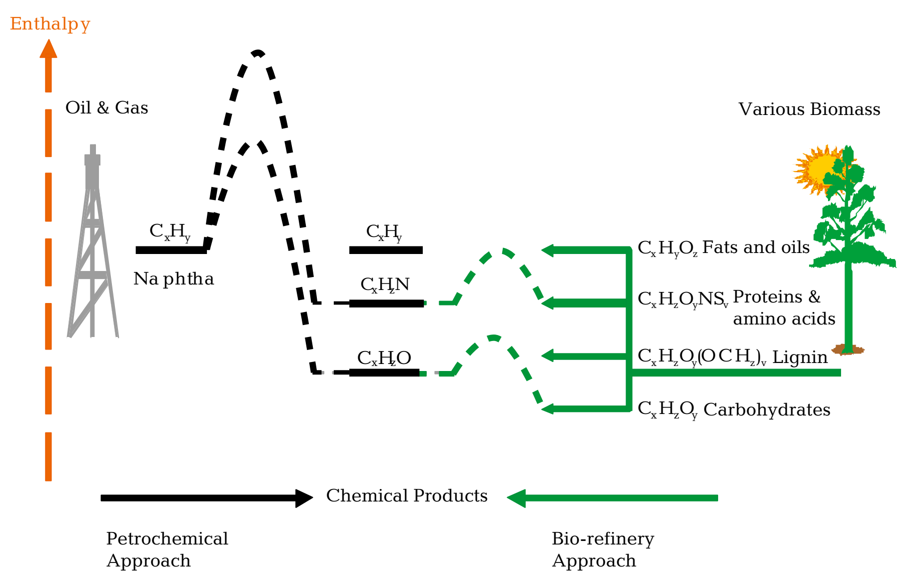
Fewer requirements to transport heat in a reactor will enable the building of smaller factories, as heat exchange capacity in factories plays a dominant role in the construction of larger plants. Because of Economies of Scale, this has been a major tool for competition between the chemical industries. However, how can we overcome the new challenges of using biomass, such as the purity of the chemical building blocks that is required for the polymerisation of polymers we know? What will be the (new) driving forces for the reactions to proceed, the solubility properties, the separation properties in membrane systems, the emission of gaseous reaction products and side products? To fulfil requirements of sustainability, we should start with various principles:

The production of biomass should take as little of the expected scarce resources as possible, such as fertile land, biodiversity, water, phosphates, and renewable and non-renewable energy. Furthermore, it should contribute to the welfare and wellbeing of the people involved in the entire production chain. Undesired competition with food supply should be prevented, but from an integrated perspective, food and non-food can be synergistic, which should be stimulated with integrated process technologies.

Current State-of-the-Art

Two approaches for the production of bulk chemicals are indicated in Figure 11. One is directed towards the base chemicals ethylene and propylene as is the case for the petrochemical industry. The other starts from molecules that can be obtained from biorefineries where the molecular structure in plants is similar to the structure now produced in several steps from naphtha. Because of the low price of ethanol in Brazil, commercial production of ethylene by Braskem has begun. Propylene produced through ethylene will soon follow. The advantages are that large volumes of cheap ethanol are available in Brazil and there is a large market volume of ethylene. However, no advantage is taken from the molecular structure of the biomass that could reduce the energy and capital cost requirements currently required for the downstream products of ethylene.

Figure 11: Bulk chemicals can be produced from biomass base chemicals, such as ethylene, following the traditional petrochemical approach or from biomass molecular structures.



Bulk chemicals are produced commercially from biomass via the biodiesel residue glycerol. The Belgian company Solvay has two factories in operation to produce epichlorhydrin, and two more factories will follow before the end of 2011. The process benefits from the molecular functionality that is present in glycerol. Dupont/Tate&Lyle/Genecor are operating a fermentation process of corn starch developed by Genencor to produce 1,3-propanediol. The functionality of the raw material also contributes to the competitiveness with fossil-derived equivalent products. ADM and Dow are preparing factories for the production of 1,2-propanediol and epichlorhydrin, respectively, from glycerol. BioMCN is producing methanol from glycerol. Cargill is a pioneer in the production of polylactic acid. Recently, Synbra/Purac began commercial production of a polystyrene substitute manufactured by foaming polylactic acid. Polylactic acid is an example of a new chemical entity that substitutes or improves the properties of fossil polymers. Several industrial companies will soon introduce succinic acid as a 'new' building block for the bulk chemical industry. Much work has been performed on the development of new process routes from biomass, such as xylene through isobutanol, acrylonitril, N methyl pyrrolidone and diaminobutane from glutamic acid; aniline from tryptophan, diamimobutane and urea from arginin. Biorefineries that can supply the right raw materials at competitive prices are being developed from the residues from bioethanol and biodiesel production.

How to progress

To anticipate a novel chemical industry based on renewable feedstocks from biomass, new technologies have to be developed, but some can certainly benefit from existing knowledge from the food industry or in the petrochemical industries from the past 200 years. However, the boundary conditions are very different than in the past, which will create new challenges.

For the production of bulk chemicals in the decades to come, cost and energy reduction compared to the traditional food industry has set our major goals. Furthermore, we should develop various ways to obtain the purity of chemical building blocks that is required to use them for downstream polymerisation reactions. Again, these separation technologies should work under low cost and energy requirements. Integration of the different conversions and separations will make use of the specificity of enzymes in their conversion of just a single component. If the conversion product has properties different from the mixture that was taken from the raw material, separation might become possible without significant cost or energy expenditure. Insolubility of reaction products is an example of the tools that we should develop.

How can we obtain the raw materials to be used as inputs for fermentation or for chemical or enzymatic conversion such as amino acids from (residual) proteins, monomeric sugars from cellulose and other plant wall components, aromatic monomers from lignin, all at low energy and costs?

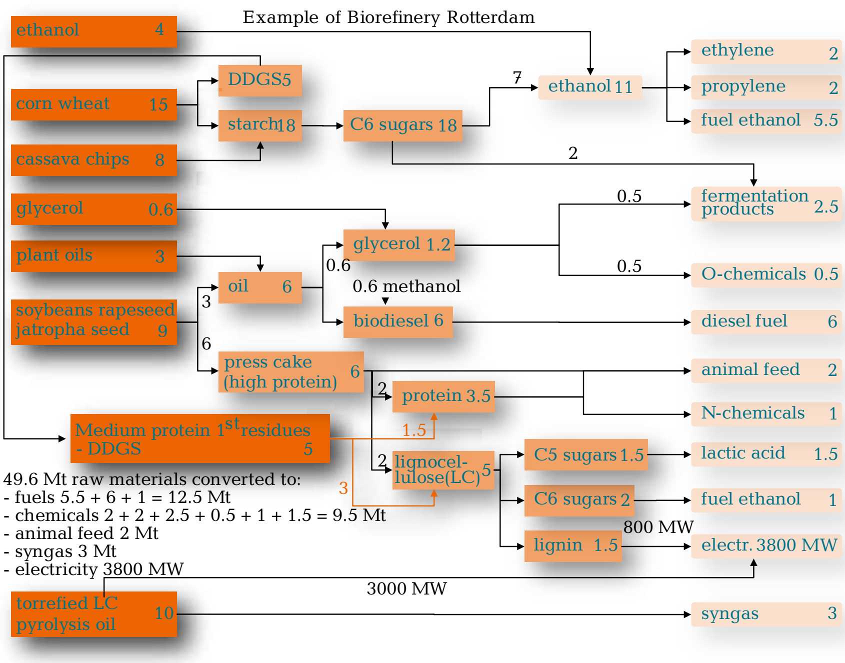
Thermal processes need to be optimised because the inputs will be used are mixtures of diverse natures and they contain S, N, P, K that might poison all known catalysts and, more often, we will start from dilute watery biomass streams. An important tool to be developed is a further understanding and definition of what we regard as sustainable production. Will this be different for different products? Will it be the same for all places in the world? We have to develop a metrics toolbox from which we can assess the sustainability of the production of the chemicals and functionalities that we desire. Above, only substitution of chemicals produced from fossil resources are addressed. However, can we develop building blocks with new properties in their polymeric form? In the fossil era, we developed molecules with the boundary conditions of availability of raw materials and intermediates, and thermodynamics. In the future, the raw materials and the intermediates will change.

Can we design novel ways of polymerisation for different sets of monomers and tools? Can we use plant polymers to develop novel polymeric products directly without breaking them down to their monomeric molecules? How can we further integrate agricultural production, separation and conversion?

Decentralised and, therefore, small-scale units close to the fields of production will be developed to enable the recycling of minerals and organic matter required by the soils to stay fertile, and only the intermediates will be taken to larger factories for further processing. Finally, the integration with plant genetics will enable the design of plants, allowing the composition and their process ability to be optimised for the downstream processes. Crops that are improved by genetic modification or by other genetic means will interact safely with the environment, as is now the case for approximately 150 million hectares of GMO crops, mainly corn, cotton and soy.

A main port of Rotterdam might look like the representation in Figure 12 in the year 2030.

Figure 12: Bulk chemical products are manufactured in Rotterdam based on biomass raw materials and intermediates (numbers in Mtonnes/year).



Research Activities Needed, 2017 Deliverables and Disciplines Involved

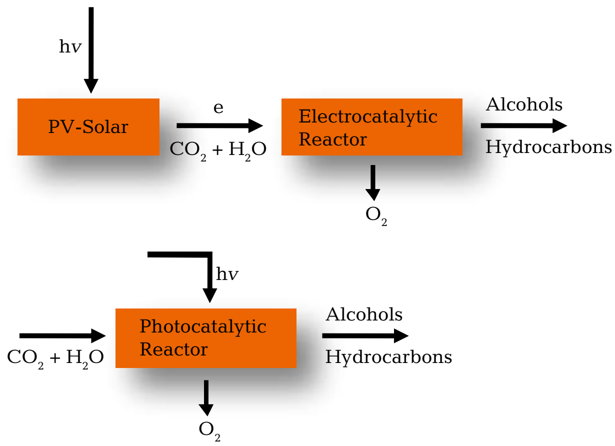
Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. Biorefinery	Energy-efficient separation of plant storage compounds (cellulose, protein, starch, lignin, fatty acids,..) for 5 different primary crops and waste streams	Process technology, chemistry, agronomy
2. Energy efficient(> 75%) synthesis and recovery of bulk chemicals	Demonstrate PoP synthesis of five bulk chemicals from polymers isolated from plants	Process technology, chemistry, microbiology/ genetics
3. Small scale recycling primary feedstock biorefinery	Understand design rules for biorefining of three crops without essential negative economic effect of small scale	Process technology, chemistry, agronomy
4. Solutions for S, N, P, K losses in thermal processes	Removal of S, N, P, K to allow efficient catalysis for three different processes	Process technology, chemistry
5. Protocol to assess sustainability of crop/ separation/conversion combinations	Five bulk chemicals including co-products assessed	Process technology, chemistry, agronomy, economy
6. Modification of plant polymers	Five cellulose derivatives to substitute starch derivatives as active hydrocolloids	(Bio) chemistry, applied sciences
7. Hydrolysis of lignocellulose and proteins to monomers	50% of costs compared to 2010, zero waste	Process technology. chemistry

12 Functioning devices for converting sunlight to fuels

Background – Why This Milestone

The world is facing a tremendous energy challenge. Since reserves of oil and other fossil fuels are diminishing at an increasing pace, and considering the tremendous environmental impact of the use of these, alternative processes have to be developed, both to provide society with sustainable energy and fuel, as well as with renewable-based chemical products. It is clear that to meet the future energy needs of the sustainable world, biomass-derived fuels and products are a step forward. However, from the viewpoint of converting solar energy into chemical energy, growth of biomass is inefficient. The efficiency is, at best, approximately 1% in locations such as Northern Europe. While for the short- to mid-term, the use of bio-fuels and bio-derived chemicals can compensate for the reducing availability of fossil feedstock, artificial solar conversion systems have greater potential. Significant advances have been made in photovoltaic technologies for the conversion of solar energy into electrical energy. However, production and demand need to be balanced both in time and across different locations, which requires the scalable conversion of solar energy into fuel as a transportable storage medium. There are various options to achieve this, and this milestone briefly evaluates these options (Figure 13), including the potential option of combining solar energy conversion with biomass-related processes.

Figure 13: Schematic representation of the process options. The second scheme can also be applied if solar energy generates heat in a solar thermal reactor



Current State-of-the-Art

Solar to electricity

Significant advances have been made in photovoltaic technologies for the conversion of solar energy into electrical energy. Over the years, different types of solar cells have been considerably improved, leading to impressive research cell efficiencies reaching 40%. In practice, in commercial modules based on silicon, efficiencies at present are always lower and on the order of 20%. At present, the cost of electricity compared to other electric power generations is not yet favourable in many cases. It varies strongly with the application and area (e.g., latitude, state of development of different countries), but generally for large-scale production, it is still 2-5 times more expensive than fossil-based electricity generation.

Electricity to chemicals

Electricity can be used to convert water into thermodynamically uphill products by electro(cata)lysis. Electrolysers for hydrogen production currently have a reasonable efficiency on the order of 50-80%, with the major efficiency loss being the large over-potential required for oxygen evolution (effectively, this leads to generation of heat). Unfortunately for electrocatalytic conversion of CO_2, the efficiency is much lower and is 1% at best. This low efficiency is partly related to the relatively low solubility of CO_2 in water and the kinetically preferred reduction of 2 H^+ to H_2. In other words, many studies of electrocatalytic CO_2

reduction show that a highly diluted stream of hydrocarbons in H_2 is obtained. While promising, integration of electrocatalytic processes with biomass conversions is rarely practised to enhance hydrocarbon production.

Solar energy to chemical energy

Several options for solar energy harvesting and direct conversion to chemical energy have been proposed and are topics of intensive research. The growth of biomass necessary to achieve this is, at best, only approximately 1% efficient. Alternative technologies for direct harvesting of solar energy without the use of living cells exist, and they can roughly be divided into photocatalysis technology (using predominantly the UV range of the solar spectrum) and solar thermal technology (i.e., the use of the IR range of the solar spectrum), both utilising solar energy to induce endothermic reactions. A highly efficient photocatalytic solar-to-fuel converter (S2F) does not currently exist. Colloidal suspensions of platinised TiO_2 in one simple reactor have been described for hydrogen production. The function of the Pt promoter on TiO_2 is two-fold: it enhances the lifetime of the photo-excited states (i.e., promotes electron hole separation, the generation of which is achieved by light absorption) and it catalyses electron transfer to H^+, forming H_2. Efficiencies are low and are on the order of a few percent at best, as a result of catalyst imperfections and the light utilisation of suitable photo-catalysts, which is usually limited to UV radiation. Currently, in solar thermal technology, solar power can be concentrated efficiently, and depending on the solar flux concentration, the optimum operation temperatures vary between 1100 and 1800 K. Very high theoretical thermal efficiencies can be reached by the direct thermolysis of water. However, the dissociation of pure water requires temperatures up to 3000 K (for 64% dissociation at 1 bar). These temperatures challenge the materials used for the construction of the reactor, and the separation of hydrogen and oxygen seems to pose an insurmountable barrier to this process. Metal-oxide cycles are more efficient. Different reactor types have been realised to meet the challenges of this process.

How to Progress

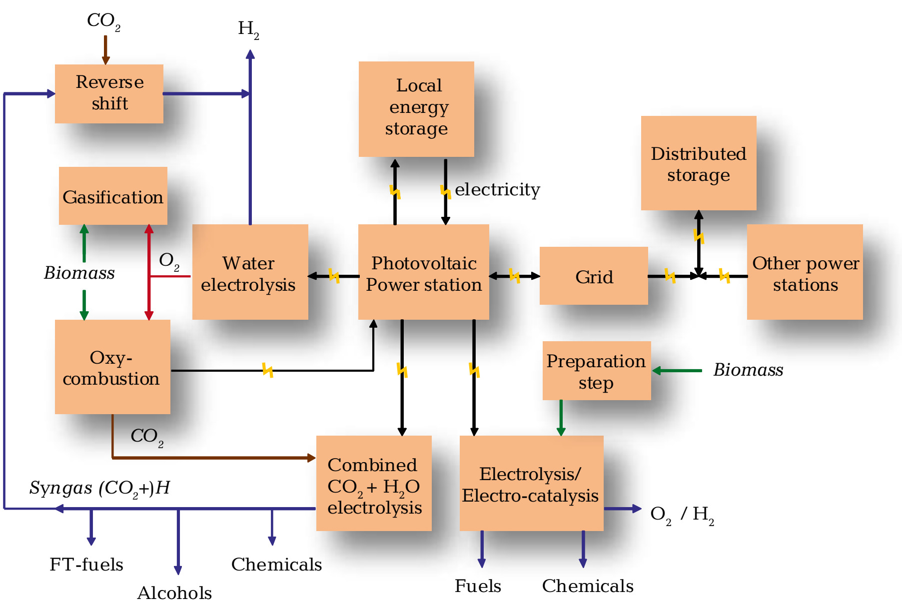
Solar to electricity

In principle, the future for photo-voltaics looks bright because of the huge potential and rapid development. Current developments cover a broad range of cell types based on crystalline silicon, multi crystalline silicon, ribbon silicon, while thin film cells are developed based on a variety of materials such as indium gallium (di)selenide. Moreover, junctions cells, light-absorbing dye cells, organic/polymer cells (multiple and silicon thin films) are developed involving nanotechnology. The module price versus experience curve shows a favourable learning behaviour and in most future projections, it is assumed that photovoltaics, in combination with the use of solar heat, will play an important role in providing electricity (10 - 50% of total production) and possibly in providing fuel. Therefore, in the very long term, it could even meet the bulk of the global energy demand. Research endeavours in this field are highly appreciated and necessary.

Electricity to chemicals

Research efforts in the next 20 years should focus on development of new engineering concepts of "Electrocatalysis", which should integrate several functional steps in combination with biomass conversion, as shown in Figure 14. Cheap and effective water oxidation electrodes need to be developed based on abundantly available elements, and catalysts are required tailored to the desired conversions of CO_2.

Figure 14: Options for integrated process operation combining biomass conversion and electrocatalytic steps



Solar to chemicals

Increasing the extent of bio-based 'normal' photosynthesis is necessary for a biological solution, and the amount of land available for agriculture can be expanded. Another strategy is to increase the efficiency of agriculture in terms of higher output per m^2. Constraints are the limited amount of surface of land available and inefficiency in biological processes, which lead to waste. An alternative to exploiting the land is to develop biological processes in water (lakes/seas), e.g., producing algae. Certainly harvesting and removing the large excess of water are challenges to be dealt with and require investigation. When photocatalysis (non-biological) is aimed for, a major challenge is to improve on the low rates that are achieved in photocatalytic conversion. Development of improved visible-light-activated systems is necessary to enhance the solar-to-chemical production rate (solar light contains roughly an order of magnitude more visible light in comparison to UV light). Significant improvements in catalyst function can be achieved if effective water oxidation catalysts can be found, such as nano-structured Co_3O_4, which is cheap and rather effective. Focus has been predominantly on materials design in the solar-to-fuel area, rather than on operational modes of the catalysts. Important improvements are also feasible if photo(micro)reactors are developed, e.g., with integrated oxygen and fuel (hydrogen) separation functions. Important steps have already been taken in the development of solar thermochemical processing. In the thermally induced conversion of solar energy, clever metal/metaloxide cycles need to be optimised. During the next decades, several pilot plant projects will unavoidably grant a new level of understanding of these systems.

Research Activities Needed, 2017 Deliverables and Disciplines Involved

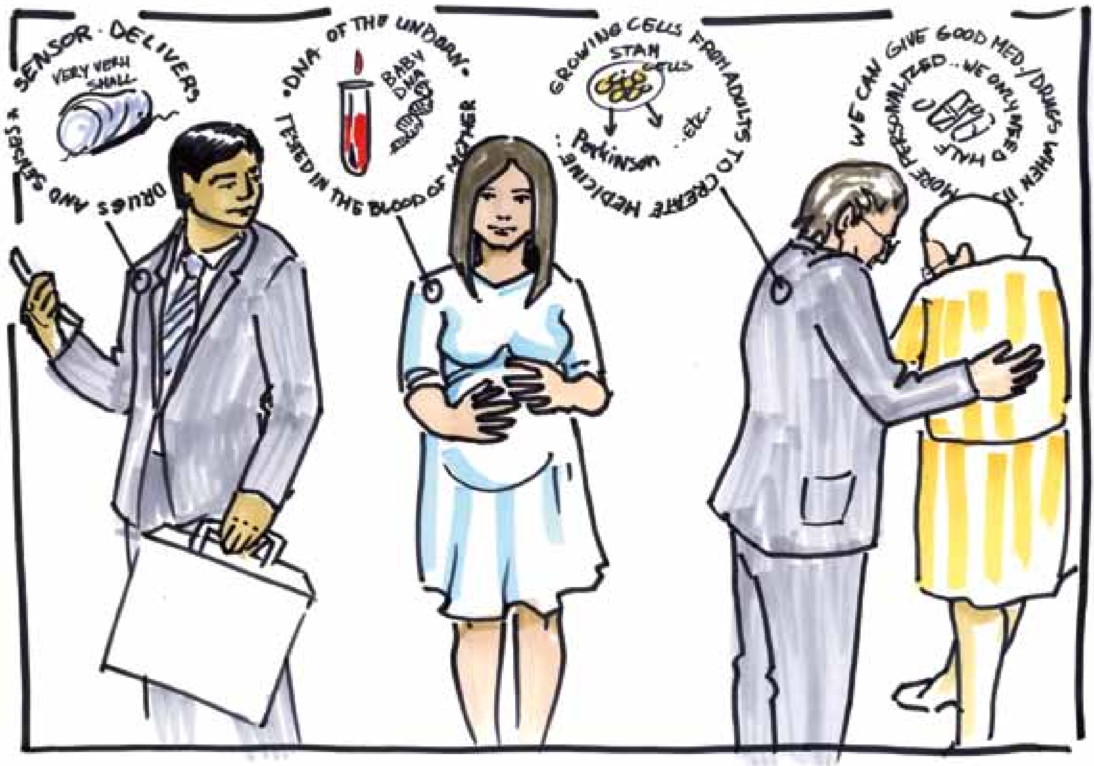
Research Objective	Deliverable, 2017	Scientific Disciplines Involved
1. PV + Electrocatalysis of H_2O (with CO_2) to fuels, in which highly efficient PV cells with efficiencies of 40% are integrated with biomass conversions. Targeted fuels should be composed of $>C_{12}$ molecules. Process should be more advantageous compared to other (biotechnological) approaches	Two to three concepts developed with proof-of-principle on laboratory scale	Materials chemistry (ceramics), electrochemistry, reaction engineering, process design
2. PV + Electrolysis of water for hydrogen production in which highly efficient PV cells with efficiency of 40% are integrated with RT electrolysers which are cheap and have efficiencies of >90% ($e \rightarrow H_2$), achievable by optimisation of water oxidation catalyst	Two to three concepts developed with proof-of-principle on the laboratory scale	Electro-catalysis, materials chemistry, reaction engineering
3. PV + Electrocatalytic CO_2 conversion, in which highly efficient PVcells of 40% and low cost, are integrated with CO_2 capture from thin air and conversion to CH_3OH or C_6^+ in a electrocatalytic reactor, more efficient than PV $\rightarrow H_2$ ($+CO_2$) $\rightarrow$ catalytic Fisher Tropsch production of fuels	One to two concepts developed with proof-of-principle on the laboratory scale	Electro-catalysis, materials chemistry, nanotechnology (micro) reaction engineering
4. PhotoCatalysis for Hydrogen combined with CO_2 conversion. Advanced Materials/Devices for Solar to Syngas Conversion keeping pace with the Solar flux, and more efficient than PV $\rightarrow H_2$ ($+CO_2$) $\rightarrow$ catalytic syngas production	One to two concepts developed and demonstrated on a molecular scale	Materials chemistry, inorganic chemistry (photo-)reaction engineering
5. Smart metal, -oxide cycles for solar thermal production of hydrogen (from H_2O) or CO (from CO_2), including advanced reactor design (risers/downers). Development of light concentrators and heat exchangers for optimisation of light and heat management. Energy efficiency of 75% (light in, chemistry out)	One to two pilot plant projects to demonstrate efficiency improvements compared to current state-of-the-art	Materials chemistry, inorganic chemistry, reaction engineering, mechanical engineering, physics, process design

Appendix

Beacons per subject area

This section includes descriptions of the beacons that were formulated in the first workshop of the Delft Skyline Debates. These beacons were the starting point for the identification of milestones.

Health



Everybody healthy!

For the first time in history

> A large class of diseases have been eliminated by prevention and cure for a world-wide population, leading to a life-expectancy of 100

> This class covers infectious diseases, cancers, genetic diseases, autoimmune diseases, lifestyle diseases etc.

This is relevant because

> Personal wellbeing
> Equal social opportunities
> Less economic loss

Questions

Who benefits?

> All people affected, especially poor in developing countries
> People with genetic disorders
> Rich without self-control

How could this work?

> Prevention: low-cost screening & self diagnostics;
better and individualized food; improved lifestyle
> Cure: personalized targeted medicines; stem cell repairs;
bionic devices

Better health by personalized food!

For the first time in history

> All people can diagnose their dietary needs for the day and buy personalize diets

This is relevant because

> No nutrition
> Imbalance of nutrition taking up
> Averaged needs are not representative
> Lifestyle diseases

Questions

What is the benefit?
> Better health and long-livety

Who benefits?
> Everybody

How could this work?
> Information systems
> Diagnostics
> Food modularization

When I'm ninety four....

For the first time in history

The quality of life is so improved that…
> Life expectancy is equal for all new-born babies irrespective of the place of birth;
> Health is excellent throughout whole life (mental and physical health)

This is relevant because

> In developing countries, life expectancy is currently less than 50 years (that is not fair!; intra and inter generational equity)
> Today, this is feasible only for a few lucky ones!
> Science and new technology can deliver

Questions

What is the benefit?
> Happiness (through better health and productivity)

Who benefits?
> Everybody, in particular developing countries and young people (the next generations)

How could this work?
> Genetic screening (preventive)
> Tailored medicines (curative)
> Low cost adaptive technologies providing for human needs (e.g. food, water, energy, shelter etc.)
> Education and research
> More equitable distribution of resources

Transport

Transport – it's electric

For the first time in history

> All land-based transport runs on electric energy based on a sustainable electricity network and/or decentralized chemical conversion system

This is relevant because

> We need to reduce oil use and gas emissions from transport and we need to reduce air pollution from transport

Questions

What is the benefit?

> Integrate all sustainable/alternative energy production methods

> People's health and healthy environment

Who benefits?

> People and ecological systems

How could this work?

> Fuel cells (multifunctional) new membranes with higher proton exchange (small-scale, onboard vehicles; producing H_2 on board from CH_4 or biomass-based liquids)

> Plug-in, plug-out vehicles feeding back into electricity system

> Improved photovoltaic system for producing energy at home

Cars from waste

For the first time in history

> The transport sector is completely sustainable – all cycles are closed including in materials and resources

This is relevant because

> Close cycles to reduce waste
> Re-use waste efficiently
> More and more people will increase mobility

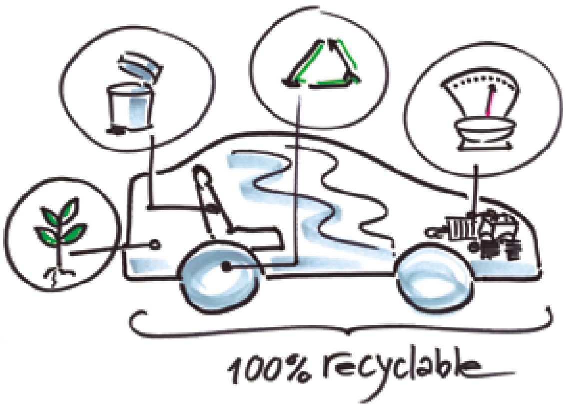
Questions

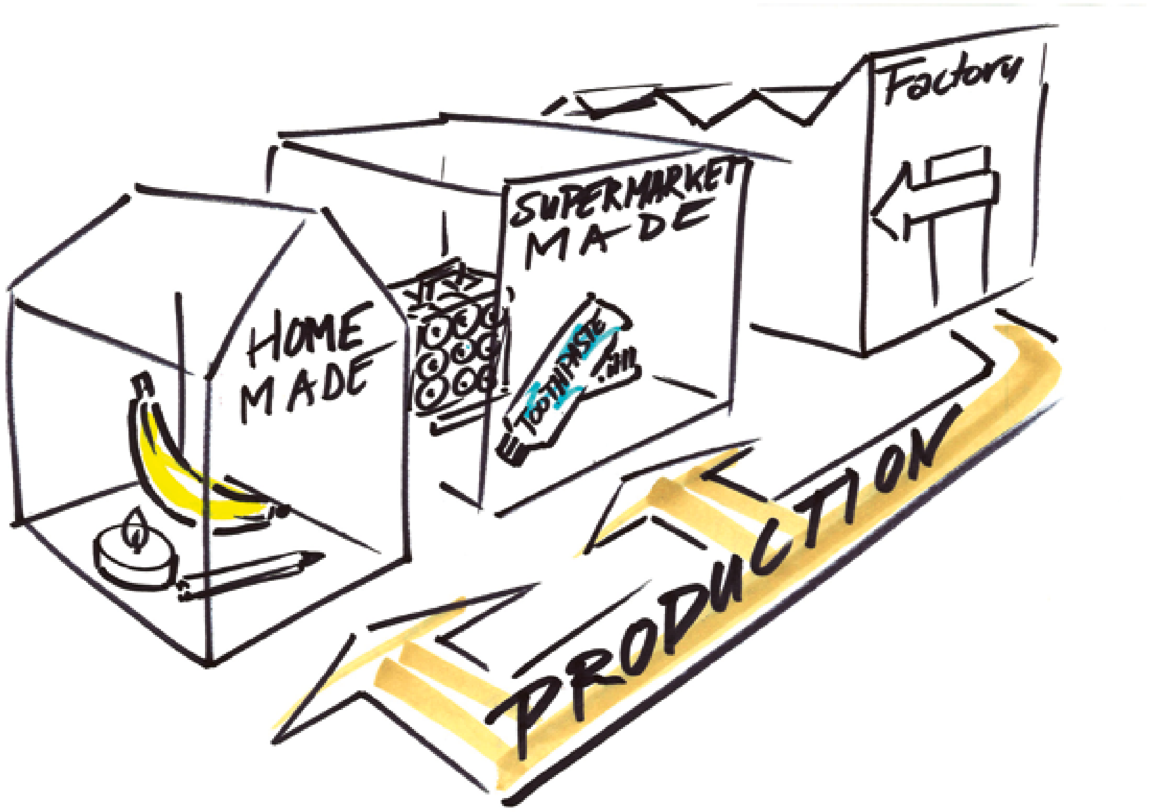
What is the benefit?

> Cheaper materials
> Reduction in resource consumption

How could this work?

> Materials – recyclable from renewable materials
> Cars from waste
> Lighter materials
> Nanostructured advanced materials (e.g. membranes for fuel cells and sensors)
> Catalyst – recyclability incorporated into design





Produce where you consume!

For the first time in history

> Most consumer products are produced in close proximity to the user from raw materials from the proximity

This is relevant because

> Transportation effort is reduced
> Waste discharge and treatment is reduced
> Consumer comfort is improved
> Diversity of substances to be handled is reduced (REACH)

Questions

What is the benefit?

> Minimize resource use (material, energy, human resources)

Who benefits?

> Individual, society, environment

How could this work?

> Products with higher functionality and less precursor product diversity
> Decentralized and scalable production technologies
> Redesign of supply chain logistics
> Decentralized renewable production

Power House

For the first time in history

> 90% of the houses produce more energy than they consume!
> Double the lifetime of houses

This is relevant because

> Major reduction (~50%) of energy consumption
> Helps environment
> Improves quality of life

Questions

What is the benefit?

> Low cost

Who benefits?

> Whole community and the environment

How could this work?

> Choice of material (appropriate and new)
> Recycling
> Integrated energy generation management
> New design strategies

Food & agriculture

Plants replace mineral mines

For the first time in history

> We can obtain 50% of all elements we use from agriculture

This is relevant because

> Almost half of the elements we use are "endangered" (<50 years from traditional resources)
> It is getting more expensive and dangerous to extract
elements from traditional resources (e.g. C (fossil), P, N, metals (Fe, Ru, Pt, Ag, Zn, Ta…)

Questions

What is the benefit?
> Elements become sustainable and affordable
> Avoids need to mine in hostile/difficult regions
> Security of supply (avoid dependency on Middle East, China, Russia)
> Continuous supply of food

Who benefits?
> Process industry and general population

How could this work?
> Genetic technology for plants and algae (several species)
- Capturing elements
- Storage
- Synthesis of chemicals
- Easy processing
Growing in stress conditions
> Product design (recyclable/recoverable elements)
> Supply chain logistics
> Biorefineries (more concentrated systems; full, optimal biomass utilisation)
> Extraction/separation technologies

Good food for all!

For the first time in history

> We will have achieved efficient and sustainable, closed-cycle production, harvesting and conversion of food, from field to consumer for every human being on earth, with a total efficiency of >50% in energy, and no waste or emissions
> The food produced will be produced on demand, according to body requirements, yielding preventive health case and quality of life
> (We will use new, efficient crops (e.g. algae) for new, enjoyable, efficient foods)

This is relevant because

> We'll have 9.5 bn people, living 100 years on average
> We want to have peaceful, stable living
> We want to have good quality of life for every year of the 100
> Fresh water availability is a bottleneck: salt water production
> Avoiding depletion by using crops as bioseparators

Questions

What is the benefit?

> Better use of energy, water and other resources
> More recycling, avoid depletion (or even revert it!)

Who benefits?

> Every human being and nature

How could this work?

> Consider salt water desalination (by crops, by technology) and water cleaning
> Use salt water crops
> Use crops as bioseparators
> Create "building blocks" (composite ingredients, see below)
> Downscale processing technology, enabling processing distributed over the chain (farm, factory, logistics, supermarkets, kitchens)

Food with less energy input

For the first time in history

> The integral energy efficiency of food production reaches 20% worldwide

This is relevant because

> Current efficiency is 5% (2500 kcal digested from 50 kW[?] input)
> It releases energy for other uses
> It enables more people to be fed
> Increases possibilities for producing food locally
> Reduces other resource consumption (water etc.)

Questions

What is the benefit?

> More food and fuel (+ other services) for more people
> Less virgin resource requirements

Who benefits?

> Consumers, farmers and the environment, worldwide

How could this work?

> Integrated bio refineries
> Localised bio refineries
> The farm becomes the factory of the future
> Energy management (in-house and in-factory; use of water heat for cooking, improved food processing, packaging)

Boundary

Energy

For the first time in history

> We are able to produce chemicals on the commercial scale using exclusively solar, geothermal or wind energy

This is relevant because

> Fuel shortages are expected

Questions

What is the benefit?

> Processes based on 100% clean and renewable energy

Who benefits?

> Mankind

How could this work?

> Region-dependent process & plant development (one has sun, the other wind or hot springs)
> Intensified methods for efficient generation, conversion and storage of various energy forms (electrical, electromagnetic, etc.)
> New concepts of plant operation and control
> …

Resources

For the first time in history

> We have managed to eliminate fully the use of non-renewable raw materials (including catalysts) in chemical processes (without competing with food on biomass)

This is relevant because

> We will fully eliminate use of fossil resources in chemical processing
> We will have a broad range of feasible renewable-based processes that do not compete with food

Questions

What is the benefit?

> Long-term survival of human race

Who benefits?

> Mankind and environment

How could this work?

> Coupling between process intensification and biotechnology
> Use of alternative energy forms in processing
> Efficient method for biomass pretreatment
> Replacement for (metal-based) catalysis
> …

Zero waste

For the first time in history

> All chemical and food processes are zero waste

This is relevant because

> We have limited resources

Questions

What is the benefit?

> Lower energy consumption and CO_2 emission
> Lower cost products
> Lower environmental impact

Who benefits?

> Industry, consumers and the environment

How could this work?

> 100% selective processes
> …

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