ChemistryNL

Roadmap

Conversion and

Process Technology

ChemistryNL

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Executive summary

Making sustainable chemical products

On top of the list of Global Challenges, we find the need for sustainable development and the necessity to address climate change. High on the list as well is the Global Challenge to sustainably meet the growing energy demand. The field of chemistry is ready to take on a key role in helping to tackle these challenges. At the same time, it will have to deal with the changes these global developments will impose on the sources of raw materials and energy which have been the basis for the chemical industries and ultimately for our society during many decades. In particular, catalysis and process technology are crucial disciplines when it comes to establishing the scientific and technological foundation for defining and implementing cleaner, more efficient, economically viable chemical production processes, and enabling a change in feedstock and energy sources to fuel our processes.

In this document, the program council Conversion and Process Technology describes how circularity and the use of bio-based feedstock will play an increasingly important role. It addresses how it will use catalysis and process technology for the production of functional molecules, materials, and (precursors for) energy carriers, making use of the current and future feedstock and energy sources. With the strongholds for these fields of expertise in the Netherlands, it is indicated how reactions, catalyst materials, reactors, and production processes shall be integrated at all length- and time scales of importance. These aspects jointly will be instrumental in retaining the competitive edge of the chemical- and catalyst industry in the Netherlands.

The overarching ambition for the year 2050 is to complete the transition from our fossil resource-dependent economy to a circular low-carbon economy that relies on sustainable and abundant resources. A roadmap is presented that includes chemical technologies to realize this ambitious goal. Technologies and innovations are essential to accomplish the required energy and material transition of the (chemical) process industries. The use of CO_2 and recyclates as feedstock is a prime example of how innovative approaches can contribute to this ambition. The roadmap outlined by the program council Conversion and Process Technology provides a clear path towards achieving these ambitious goals by 2050.

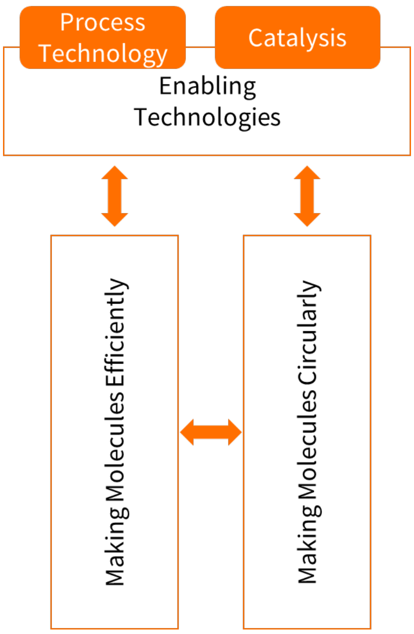
1. Introduction

Chemistry in all its facets is the most important enabler of technologies and processes that contribute to a more sustainable, healthier world. ChemistryNL aims to work on solutions for major societal challenges, based on green chemistry, circularity, and a biobased economy. To arrive at the best solutions, ChemistryNL actively encourages companies, universities, research centers, and governments to work together on knowledge and innovation.

The roadmap Conversion & Process Technology focuses on the development of efficient (bio)chemical processes and separation technologies without waste production. The scientific knowledge generated serves two purposes; Societal challenges on the one hand call for focused innovation while scientific challenges require a strong knowledge base of the underlying (chemical) disciplines. Both goals are highly complementary and form the basis of the two chapters in this roadmap.

The societal challenges are described in chapter two and are divided into two themes:
- *Making Molecules Efficiently*, which focuses on creation of efficient (minimal resources using) processes per sé (large volume products are the dominant application field).
- *Making Molecules Circularly*, which focuses on, as high as possible, the re-use of molecular material, supplemented (if necessary) by bio-renewable feedstock.

The scientific and technological challenges are described in chapter three and are divided into two disciplines:
- *Process technology*
- *Catalysis*



The roadmap promotes multi-scale understanding and developments all the way from active sites (nm), particle agglomerates (µm) to catalyst particles (mm), to reactors (m) and the refineries or chemical plants in which they are integrated, as well as the time-scales governing chemical reactions (ps) via transport phenomena (ms) to the complete lifetime of a catalyst (minutes to years). In addition to the dimensions, understanding how these existing (infrastructural) systems are linked also yields valuable information. Indeed, understanding these systems can help to find the right approaches to enable the energy and material transitions that we currently face. This is especially true for developments where materials that have been used as an energy carrier are now recycled to simultaneously serve as feedstock. Such chemical knowledge can be used in transdisciplinary research that is the basis for a new policy that targets system-wide changes.

The contents of the roadmap fit into the program of Horizon Europe, displaying significant overlap with Horizon Europe's Cluster 4 (digital, industry, and space). Relevant calls can be found in themes like manufacturing technologies, circularity of resources, electrification, and climate-neutral industry. The main purpose of this roadmap is to structure funding for national innovation programs. The previous version of this roadmap was a base for the knowledge and innovation agenda’s (KIA), now the contribution of this roadmap to these KIA's is stressed.

1.1 Why should we do this?

The continuous growth of the world population results in various social issues such as a huge increase in demand for energy, clean drinking water, and consumption goods. To meet these demands and at the same time reduce the use and reliability of fossil resources, or even more so, transform to a CO2 neutral industry and society, huge challenges and calls for breakthrough innovations are inevitable. Creating a sustainable energy supply with minimal use of fossil fuels and rendering our industries circular by using sustainably sourced raw materials are some of the most important challenges at this time. Here, chemical research and industry play a key-enabling role in the transition that our society has to make. Meeting these challenges will be essential to ensure a healthy future for the world population, to preserve biodiversity, and protect our planet.

The Climate Treaty of Paris has been an international effort to limit global warming and has led to European and national initiatives. Europe is striving for a climate-neutral economy in 2050 by implementing the Green Deal with the first milestone set in 2030. The Netherlands has formalized this into the raw materials and climate accords (grondstoffenakkoord en klimaatakkoord) with similar deadlines.

1.2 How is this relevant to the Netherlands?

The research directions proposed in this document relate to the Missions as described in the Knowledge and Innovation Agenda. They will contribute to more efficient use of resources, resource recycling, reduction of waste and CO2, and conversion of waste to useful raw materials. This will create jobs (possibly for highly educated people), and promote resource independence, as well as novel sustainable routes to biomedical, food, feed, fertilizers, and specialty products. It will lead to increasing use of progressively lower-cost sustainable resources, and improve European competitiveness towards Asia, USA, and the Middle East.

The Chemical industry in the Netherlands generates an approximate annual revenue of 64 billion euros, and with this, the Netherlands is the fourth largest chemical producer in Europe and tenth worldwide. About 46,000 people are employed in the chemical industry (source: CBS). The Netherlands combines its strong process industry with a concentration of catalyst and enzyme producers, the importance of which is clear from the fact that about 85% of all chemicals are made through catalytic processes. The Industrial players are closely involved with the Dutch academia which are traditional strongholds in the fields of catalysis, (bio)catalysis, organic synthesis, process engineering, and downstream processing. Synthesis of functional materials (e.g. bioactives developed in SME’s), and polymeric materials (through homogeneous or heterogeneous catalysis or fermentation), is a strongly developed field.
Academic research in the Netherlands in the mentioned fields is of world-class status. Industry involvement in academic research is demonstrated by the active participation in public-private partnerships. PPP's with multiple industries involved are much less atypical in the Netherlands than in the countries surrounding us, enabling programs that can lean on broad support.

In addition to the above, the infrastructure in the Netherlands is ideally suited for the realization of a circular economy. The infrastructure in the ARRRA (Antwerp-Rotterdam-Rhine-Ruhr-Area) cluster is well equipped to handle large amounts of biomass (wood and straw type). The agricultural knowledge provides very high production yield crops (e.g. 15 ton sugar per acre). The combination of seaports, green energy (electricity) supplying providers, and big refineries gives the energy integration required for successful biorefineries but also for electrified chemical processing.
The characteristics of the chemical landscape, as illustrated above, make it obvious that investments in research and innovations in this field are of great importance. Not only does The Netherlands have the right infrastructure to be successful in these innovations, but such investments will at the same time be of key importance to maintain our industry to be successful and competitive. It will be the only way to guarantee this sector makes the transition to sustainable processes and to meet the goals as have been laid down in the climate treaty of Paris the raw materials and the Dutch climate accords (grondstoffenakkoord en klimaatakkoord).

2. Themes

2.1 Making molecules efficiently

In 2050 the majority of chemicals will no longer be synthesized with the use of fossil fuels. Chemists and chemical engineers are striving to produce molecules more efficiently both in terms of greenhouse gas reduction and efficient material use. Furthermore, alternative routes using biotechnological approaches are also being pursued. Efficiency goals are set for both greenhouse gas reduction and material use. The greenhouse gas reduction goal for the Dutch industry is 59% CO2 eq reduction in 2030 compared to 1990 and climate-neutral production in 2050, as described in the industrial part of the Dutch Climate Agreement (klimaatakkoord, deel C). Approximately 50% circular production of plastics is anticipated by 2030-2040. The final goal is that by 2050 we have established a complete circular economy (grondstoffenakkoord). These goals are rather ambitious and require the implementation of research advances in an industrial setting on the short term.

At the industrial level, we define three categories of actions to produce molecules efficiently:

1. Development of efficient production routes (choice of fundamental conversion steps (info from catalysis discipline), choice of reactor and separation concepts)
2. Integration of heat pump technology and heat network optimization, control optimization, insulation optimization, industrial symbiosis, and regional heat networks to increase efficiency
3. Decarbonization of energy carriers, by means of CC(U)S (carbon capture, utilization, and storage) and renewable energy (electrification of industrial processes)

These categories are interlinked and can strengthen each other, but are surely not mutually exclusive.

Developing efficient production routes

The Dutch industry is in general built between 1965 and 1985. Consequently, the technology applied is one that was already proven in 1970. In the meantime, new insights are gained on how to produce more effectively. Developing efficient production routes requires the type of technology development as described in MMIP 8. (Elektrificatie en radicaal vernieuwde processen).

The relevant chemical key technologies are process technology (ST[1] 5-1), (advanced) Reactor engineering (ST 5-2), Separation technology (ST 5-3), Catalysis (ST 5-4), and Electricity-driven chemical reaction technologies (ST 5-6).

The key chemical technologies listed above enable us to completely redesign factories allowing us to significantly reduce energy use that is presently necessary to separate main- and by-products by assuring that a reactor only produces the required product within spec without the need to upgrade the product streams using a combination of separation technologies. Or it allows us to replace a separation unit with more energy-efficient technologies.

Developing efficient production routes is not only relevant to increase the production efficiency of current production facilities but also to the production facilities that are being developed to produce circularly as described in MMIP 6. To balance the energy and the material efficiency it is important to reduce the production of CO_2 as much as possible. Subsequently, this calls for maximum molecular valorization of other carbon sources such as plastic waste streams, biomass, CH_4 as well as CO-containing streams. To convert CO_2 to useful hydrocarbon molecules it is important to make sure that the reduction of oxygen is carried out as energy efficient as possible, instead of applying hydrogen that is produced using electrolysis. This approach is the very basis of MMIP 13. (Een robuust en maatschappelijk gedragen energiesysteem).

[1] A number of key technologies have been defined, an overview can be found in the appendix.

Efficiency steps

The technologies required to carry out the steps in this category are in principle known: heat-exchanger network- optimization, heat-pump-technology and heat-transformer integration, insulation and control optimisation, industrial symbiosis, and regional heat networks. The challenge is to apply this knowledge in an integral way to minimize energy use and maximize material efficiency. Furthermore, the range of temperatures and temperature-lifts that can be enabled has to be pushed higher. Experience with lesser-known principles like the Stirling motor as a compression principle has to be explored. The identification and thermodynamic characterization of climate-safe working media that are adequate at high temperatures deserve further attention.

Solid oxide electrolyzer (SOE) technology is of relevance for producing hydrogen from steam, syngas from CO_2 and steam (so-called co-electrolysis), and CO from CO_2. The main advantage of the SOE technology is that a lower energy consumption is needed for the transformation due to the elevated temperatures. This technology can be further integrated (including by heat exchange) with industrial processes. The challenge is amongst others scaling up and improving durability and reliability.

The outcome of the application of these efficiency steps allows for the most cost effective part of MMIP 7. (CO2-vrij industrieel warmtesysteem) and contributes to MMIP 13. (Een robuust en maatschappelijk gedragen energiesysteem).

The key chemical technologies are heat-pump technologies like MVR, high-temperature heat pumps (ST 5-6), and heat transformers (ST 5-1/ST 1-1).

Decarbonisation of Energy carriers, by means of CC(U)S, renewable energy

Decarbonisation of Energy carriers, by means of CC(U)S, renewable energy to realize the goals described in MMIP 7 (CO2- vrij industrieel warmtesysteem) and contribute to MMIP 13. (Een robuust en maatschappelijk gedragen energiesysteem). The research goals in this category are in the field of system integration.

The challenge is that a large part of the national energy consumption is consumed by industry and that this industry is designed to produce on a very large scale, continuously 24 hours a day for years without interruption. This was possible by an endless supply of carbon fuels.
The second challenge is to valorize the quality of the energy sources applied to their thermodynamic optimum. For example, although the total amount of energy is by definition constant, the potential to do work reduces when applying electricity in low-temperature applications.

Decarbonisation of this energy supply is for a limited number of years possible by capturing the CO2 and storing it in depleted natural gas fields. This storage capacity is limited but offers a way to drastically cut emissions in the short term. Separation technologies reducing the energy intensity and increasing the quantity as well as the purity of CO2 captured, are very important because the capture of CO2 still requires a lot of energy.

For the long term, the challenge is to connect the industry with its enormous continuous energy demand to the less continuous supply of sustainably harvested renewable energy. Part of this connection will require a significant lowering of this energy demand as described under "Developing efficient production routes", partly by increasing the flexibility of the processes, and partly by converting electricity into energy carriers that can be stored more easily.

The key chemical technologies related to the decarbonization of Energy carriers are Separation Technology (ST 5-3) and Electricity-driven chemical reaction technologies (ST 5-6).

Expected results present – 2050

Societal goal:

- climate neutral in 2050 (klimaatakkoord)
- circular economy in 2050

Milestones:

- greenhouse gas reduction goal for the Dutch industry is 59% CO2 eq reduction in 2030 compared to 1990 (klimaatakkoord, deel C)
- approximately 50% circular production of plastics by 2030-2040.

Industrial end goal:

- climate neutral production in 2050 (klimaatakkoord, deel C)
- circular production of plastics by 2050

2.2 Making molecules circularly

Where “Making Molecules Efficiently” is focused on reducing scope 1&2 emissions, “Making Molecules Circularly” is focused on reducing scope 3 emissions - often the majority of the CO2-footprint of the chemical industry. In The Netherlands, the majority of carbon-based chemistry starts with naphtha cracking. To achieve drastic reduction of the CO_2 footprint, circular concepts are needed that can reduce the amount of naphtha required. These concepts can be related for example to polymers, biomass, metals and carbon dioxide itself.

Circular polymers

The current situation on polymer recycling relies on two main approaches: mechanical recycling (aimed at winning the material back from waste streams) and chemical recycling (aimed at winning monomers or otherwise valuable chemicals back from waste streams). Chemical recycling includes depolymerization (chemical or enzymatic), (catalytic) pyrolysis and gasification. From a scientific point of view, four main topics still require particular attention in terms of developing new concepts on a fundamental level:

I. Recycling of crosslinked structures (rubbers and thermosets);
II. Improvement of molecular efficiency of chemical recycling by catalysis & electrification;
III. Upgrading the current recycling approaches for thermoplastics suffering relevant side-reactions during processing (for example degradation);
IV. Combining different waste streams into polymer blends possibly to be optimized via reactive extrusions strategies.
V. Energy efficiency of solvolysis/dissolution (waste to solvent ratio, solvent recovery, etc.)

These main topics tap into most steps of the circular value networks/circles that need to be created out of the current linear value chains: collection, sorting, separation, recycling, production and use-phase. Integration of the “supply chain” for waste materials both from post-consumer as well as industrial streams seems to be a condition *sine qua non* in order to define, among others, decision models for the allocation of given waste streams for mechanical and/or chemical recycling.

In general, significant advances are required in the collection, sorting and separation of waste streams (for example in the field of sensor technologies and Artificial Intelligence for data & image processing). After collection and physical separation into various polymer streams, meticulous characterization is needed in order to identify the impurities remaining in the material. The (identification and) removal of low-molecular weight compounds is the low hanging fruit, for both mechanical and chemical recycling. The removal of molecular impurities (e.g. oxygenates, halogens) is especially important for chemical recycling, as these might decrease catalyst activity, result in fouling or the formation of potentially explosive compounds/mixtures (with consequences for process design). In case of polymeric impurities (e.g. PP in PE), identification of the kind of material (simple polymer blend as opposed to co-polymers) is crucial in devising further strategies. Low-cost and efficient characterization is paramount for cascaded use of waste streams in different recycling strategies. Furthermore, it provides input for design for/from recycling (both mechanical as chemical).

It must be stressed that material recycling aims (generally) at prolonging the lifetime of a given material, possibly also with the addition of downcycling steps, which are still possible as we often overdesign our polymeric products. Mechanical recycling is typically limited to few cycles in view of side reactions taking place during recycling and affecting ultimately the end product properties. Although this extension of lifetime is relevant in decreasing the carbon footprint (mechanical recycling is typically not energy demanding), ultimately the quality of the recycled material will become insufficient even for simple applications. As a consequence chemical recycling (with possible expansion to biochemical routes) is inevitable and should be encouraged to reach higher TRL levels for widespread industrial application.

In view of CO_2-reduction, molecular efficiency of the (chemical) recycling technologies is of paramount importance. With a low efficiency, waste is generated, or the carbons are utilized as an energy source (with CO2 as a consequence). Fundamental research on the use of (heterogeneous) catalysis combined with electrification strategies (microwave, plasma, electrons/photons) for the depolymerization of plastics into monomers (feedstock recycling) is required, focused on carbon recycling. An interesting avenue could be the use of kinetic/chemo-mechanic catalysis for (chemical) recycling purposes.

For composite materials, without a chemical bond between the matrix and the filler, selective separation could be deployed. Different strategies could be needed for thermoplastics and thermosets. Furthermore, copolymers cannot per definition simply be separated in the individual blocks. Straightforward application of these materials as compatibilizers for polymer blends might be considered a valuable option that dovetails strategy III (vide supra). Identification of other application routes for these copolymers should be further investigated.

When dealing with post-consumer waste, it is worth noticing how the relative production volumes still point to a few classes of polymers (polyethylene, polypropylene, poly(vinyl chloride), polyethyleneterephthalate, polystyrene etc.) as the major contributors, in volume, to the waste. Hence, novel circular strategies should be effective for these polymer types, but also remain applicable to novel (bio-based) polymers that are currently being developed (in light of the circular bio-based economy).

Circular (functional) chemicals

There is an obvious major demand for, and push to, more efficient and lower footprint chemical processes. To a large extent this relates to already existing molecules with an existing function. It should however be realized that the current set of industrial scale molecules is largely based on a historic context: derived from (easily) available fossil raw materials and with the function mostly discovered by empirical testing. In the coming decades the necessity to introduce molecules on industrial scale, with a pre-requested and designed function and based on renewable (CO2/bio-based or recyclable) raw materials, is eminent. This holds for small molecules as end product: e.g. 'customer-oriented functionality' such as drugs, crop protection agents, flavor & fragrance, dyes, as well as for all kinds of 'industrial-oriented functionality', such a lubricity, anti-oxidation capacity , repellency etc. It also holds for small molecules that act as monomers for (new/adapted) polymeric materials, current relevant examples include: furandicarboxylic acid (FDCA), lactic acid, isosorbide.

Synthesis is at the heart of making novel functional molecules. Synthesis can be strengthened with Artificial Intelligence (and/or Machine Learning) to arrive at 'reinforced monomer/polymer design'. Furthermore, synthesis is in interplay with the disciplines 'Catalysis' and 'Process technology' (chapter 3). The key chemical technologies related to circular polymers are Artificial Intelligence (ST4-1), Separation technology (ST5-3), Catalysis (ST5-4) and Sensor and actuator technologies (ST8-1).

Circular critical and finite materials

Conservation of our elementary building blocks is needed to ensure their application in sustainable technologies, prevent chemical pollution and preserve biodiversity. This can only be carried out by exploiting a truly holistic and circular approach in the production, use and recovery of these materials. The development of green chemistry that enables the reuse of critical elements, molecules and materials is therefore key, next to preventing chemicals from entering the environment by safe and circular design of molecules and materials.

The fifth iteration of the EU Critical Raw Materials (CRM) List contains 34 materials: Antimony, Arsenic, Aluminum/Bauxite, Baryte, Beryllium, Bismuth, Boron/Borate, Cobalt, Coking Coal, Copper, Feldspar, Fluorspar, Gallium, Germanium, Hafnium, Helium, Heavy Rare Earth Elements, Light Rare Earth Elements, Lithium, Magnesium, Manganese, Natural Graphite, Nickel, Niobium, Phosphate rock, Phosphorus, Platinum Group Metals, Scandium, Silicon metal, Strontium, Tantalum, Titanium metal, Tungsten and Vanadium. The availability of these critical raw materials within Europe is under stress, as most of these materials are not mined and/or refined within the EU. The EU's largest reserve is the urban mine, therefore, recovery and recycling are of strategic importance, requiring innovation in (bio-)chemical recycling techniques.

Many metals and materials are of great economic importance for the Dutch and EU industry, in particular for the high-tech and clean energy applications. For some of these materials, the EU is highly dependent on a small number of countries, posing an increased supply risk. As a result of these two factors, many metals and materials are considered critical, e.g.: rare earth elements, in particular neodymium (Nd) and dysprosium (Dy) in permanent magnets for electric motors/generators in wind turbines and electric vehicles; cobalt and lithium for Li-ion rechargeable batteries for electronic products/equipment and electric vehicles.

The industrial recycling value chain involves multiple interconnected steps: collection, sorting, mechanical treatment, physical separation, and chemical/metallurgical refining. While the Dutch collection and sorting infrastructure is mature, there is a clear knowledge, technology and infrastructure gap in the recycling of CRMs present for these sorted end-of-life waste streams. The main challenge lies in their dilute use as "minor constituents" in the bulk materials (e.g. minor alloying elements, coatings), or relatively small or tiny components in a large equipment or product.

Biochemical elements like carbon, nitrogen and phosphorus face different challenges. The disposal of these elements have pushed three of the sustainability targets (Steffen, Rockstrom et al. Science 2015, 347, 736) into unprecedented territory, namely: extinction rate (one of two indicators for biosphere integrity), atmospheric carbon dioxide (an indicator for climate change), and the biogeochemical flow of nitrogen and phosphorus, of which the latter three can be solely ascribed to the chemistry of three elements: (C, N, P). Urgent action therefore needs to be taken to return to safe operating space in these processes.

Therefore, next to advancing resource management, sustainable chemistry is also urgently required to tackle environmental waste issues. For carbon, this mainly concerns the greenhouse gasses carbon dioxide and methane that are expelled to the atmosphere. The nitrogen waste issue is caused by nitrogen oxides (N2O, NOx) and predominantly ammonia (NH3) that are discharged into the aquatic environment and/or atmosphere. For phosphorus, it concerns phosphate, which is in addition to ammonia essential for plant growth, yet this building block of life also ends up in aquatic systems causing eutrophication. Ironically, C, N, and P are key players in the suite of major biogenic elements, often termed 'CHONPS', needed in large quantities to make living organisms, but also contribute heavily to three of the most stringent environmental concerns.

The key chemical technologies related to circular critical elements are Energy Materials (ST1-1) and Separation technology (ST5-3).

Use of biomass as circular feedstock

Bio-based feedstock (e.g. biomass) is a renewable (sustainable) heterogeneous resource consisting of functional molecules (polysaccharides, lignin, proteins, lipids) formed by nature out of CO_2, water, nutrients and sunlight. Bio-based feedstocks are used since the dawn of mankind for e.g. food, feed, heat and construction materials. More recently it was realized that bio-based feedstock could also be a sustainable source for chemicals, fuels and materials like polymers. However, care has to be taken that its use for these purposes does not compete with its use for food and feed (i.e. the food vs fuel discussion), and thus contributes to further conversion of nature to cropland (land use change), a major contributor to biodiversity loss.

To make efficient use of the molecules present in bio-based feedstock, a biorefinery approach to efficiently separate the different components and, when needed, convert them further to the desired products, is needed. When doing so three prerequisites have to be satisfied:

1. do not endanger food/feed production;
2. use the feedstock to its highest value;
3. make molecules/products which can be recycled (i.e. connect to a circular economy) or that replace fossil-based products that cannot be recycled (e.g. paints, coatings, lubricants, rubber, etc.).

Although examples exist of high TRL biorefinery approaches and of products that even made it to commercialization (e.g. polylactic acid), the large scale use of biorefinery approaches which can outcompete the large scale use of fossil resources in an oil refinery is limited. This is mainly related to the low yields, high energy inputs and too specific approaches for each bio-based feedstock which all relate to the complex nature of bio-based feedstock. Here clear improvements need to be made. This does not only require new scientific and technological breakthroughs, but it also requires new value chains in which 'unconventional partners' like bio-based feedstock producers, food industry and chemical industry collaborate.

To achieve the use of bio-based feedstock on a large and economically viable scale different steps need to be made:

1. Application of novel (bio-)catalytic processes that reduce the high energy inputs and increase the yields of biorefinery operations, whilst working with a variety of (less pure) bio-based feedstock. Since (bio)catalysis is a core element it will be discussed separately.
2. Development of new biorefinery and separation technologies to produce products based on their required functionality rather than on their purity. This is expected to result in lower energy input and less processing steps.

3. Development of new value chains that use bio-based feedstock without endangering food/feed production.
4. Development of novel bio-polymers (e.g. polyesters) that can efficiently be produced from biomass, can be recycled and outperform current fossil-based polymers. Here AI/ML approaches can accelerate design.

The key chemical technologies related to Use of biomass are Soft/bio materials (ST1-4), Artificial intelligence (AI, ST4-1) Process technology (ST5-1) and Catalysis (ST5-4).

Use of CO2 as circular feedstock

The last 10 years significant progress has been made in creating basic knowledge on the conversion of CO_2 into value added materials. CO_2 could be one of the carbon sources of the future. By 2050, materials and chemicals will most likely still be based on carbon, therefore, the use of CO_2 as a circular carbon source is of interest. The challenges related to the conversion of CO_2 are:

- energy efficient conversion and highly selective conversion integrated with adequate separation technology
- integration with renewable energy landscape
- modular and smaller scale process units
- integration with CO_2 capture

Electrochemistry, catalysis, biotechnology and photochemistry will be relevant for the development of suitable conversion methodology. CO_2 utilisation can benefit from large scale renewable electricity production. Nevertheless, continuous life cycle assessments are needed to judge the sustainability of the conversion method.

The key chemical technologies related to circular carbon are Catalysis (ST5-4) and Electricity-driven chemical reaction technologies (ST5-6).

Expected results present – 2050

Societal goal:

- Demonstrated integrated polymer recycle concepts based on physical and (bio)chemical recycling methods
- Creation of new technology cradle to cradle chains which could be integrated into the current polymer producing industry
- Demonstrated conversion routes for maximum recovery of all fractions' biomass value (targeting from high-value products to fuels and energy).
- Demonstrated CO_2 conversion processes, related to the production of specialty chemicals
- Security of supply dilemmas (e.g geographic) of key metals de-risked
- Demonstrated relevance of biobased and recycled streams for high performance materials and chemicals including concrete examples of this approach
- Cost-effective end products with lower environmental impact of chemical manufacturing (measured against internationally consolidated measurement system)
- Conservation and creation of knowledge-intensive jobs in the fields of the manufacturing of special/fine/pharma chemicals as well as high performance materials
- Intrinsically safe and resource and energy efficient production of fine and specialty chemical molecules/products.
- Security of supply dilemmas (e.g geographic) of key complex chemicals de-risked.
- Simplified logistics / shorter supply chains

Industrial end goal :

- Fully integrate waste, recycled and biobased streams in the monomer selection step for chemical product design
- Sustainable and robust manufacturing of any required end product through catalytic processes using abundant and renewable raw materials;
- A leading position of the Netherlands and Europe in the production and supply of fine and specialty chemical molecules/products as well as high performance material

3. Disciplines

3.1 Process technology

As mentioned in the previous chapter there are two very demanding ambitions set to make the process industry more sustainable:

- climate neutral in 2050
- circular economy in 2050

The discipline of Process Technology (PT) will play an important role in implementing the innovations required to realize these goals. We will describe more in detail the envisioned progress in four disciplines of PT: transport phenomena, reactor engineering, separation technology, and process systems engineering.

Transport Phenomena

Advancements in the area of transport phenomena, including powerful computational techniques, high-resolution measurements, and the increasing availability of time-resolved data sets, will continue to support the development of chemical processes in the coming decades. A detailed fundamental understanding and control of the transport of species (small molecules, biomolecules, ions, particles, cells) and energy (heat, light, etc.) at multiple length scales remains crucial for the deployment of new technologies. For instance, emerging technologies for (electro)chemical conversion are dominated and limited by new types of physical transport phenomena that are not considered in the “classical” chemical engineering toolbox (e.g., electrokinetic transport). Careful consideration of such transport limitations is essential for scaling up strategies. Similarly, novel processes based on biomass as feedstock require an improved understanding of multiscale transport phenomena of large molecules and molecular aggregates/complexes in (bio)reactors, with dramatically decreased mobilities/diffusivities and increased sensitivity of the transport and material properties of local temperature. Moreover, there is an increasing interest in the development and usage of complex bio-based materials, which requires further development of multiscale methods that can link molecular structure and transport to macroscale material properties. While gas and liquid flows have already been studied for decades from first principles, the field of multiphase flow has remained rather empirical. Specific attention needs to be devoted to enabling detailed (multiphase and/or reactive) simulations at larger, and preferably, industrial scales to facilitate scale-up (preferably experimentally validated). It is expected that artificial intelligence/machine learning methodologies can play an important role in the development of phenomenological/reduced-order models suitable for scale-up.

Novel algorithms, strongly increased computational power, and advanced measurement techniques (such as tomography with high temporal & spatial resolution) will enable the extension of rigorous descriptions of transport phenomena in powder flows, bubble flows, emulsions etc. Finally, the development of transport phenomena for micro- and nanosystems will be crucial to support sectors such as micro-electronics and nano-medicine. In such systems, we often operate near the boundary between a continuum and a discrete description, which requires a dedicated approach.

Reactor Engineering

The upcoming transitions in the process industry also have important consequences for chemical reactor engineering as a discipline and require novel research directions in this area. A more intermittent energy supply and more varying feedstock will enforce that reactors can deal with dynamic operation and complex flows, as well as variations in production capacities. To completely decarbonize the (chemical) process industries, the currently used heating via combustion of natural gas has to be completely phased out, requiring electrification of all processing (reactor/separation)

units to enable direct use of sustainable energy, e.g. via induction, microwave or resistive heating. Novel unit configurations, operation, and control systems need to be developed, including novel ways to establish efficient heat integration. For the electrification of the chemical industries, strong collaboration with electrical engineering for efficient energy conversion systems at industrial scales will be required. In addition, process intensification will remain an important area, developing reactors that have integrated other functions, such as separation, next to the chemical reaction. Novel ways of supplying energy to reactors (electrocatalysis, photocatalysis, plasma, high-gravity) will find their way from the laboratory to industry.
Structuring of reactors will increasingly be applied since this can either boost the efficiency (e.g., higher mass transfer) or because the energy supply requires this (e.g., electrode plates). 3D printing and other additive manufacturing approaches to make reactor internals or complete reactors will become increasingly important, as well as the treatment of these surfaces to optimize their functionality (catalytic, self-cleaning, etc.). In an increasing number of cases, the distinction between catalyst particle and reactor will vanish (like it is already the case for the three-way catalyst). Due to the increase in the number of parameters for optimization, it can be anticipated that novel machine-learning tools will be of great importance. In some sectors, such as the pharma industry, the transition from batch to continuous processes will continue. A gradual transition from bulk chemicals to high-value materials (e.g., nanostructured products) with varying properties will require the development of novel, more flexible reactor types. Renewed attention for scale-up approaches will be required, as for certain reactor types (electrolyzers, micro-, and millifluidic systems) simply enlarging the volume will not work.

Separation Technology

For high volume production applications approximately 50% of the total production costs are needed for separations, so the applied technology is a very important aspect in a wide range of industries, such as the energy sector, the water sector, the chemical industry, and agro, food and feed. To add, recent developments require chemical facilities to work towards zero waste into the surrounding environment. By implementing closed-loop systems without losses of materials and persistent pollutants (e.g. microplastics and PFAS) in processes can contribute to minimize waste and increase circularity within chemical facilities. Moreover, integrating advanced filtration and treatment technologies in wastewater management can prevent these pollutants from entering the environment.

The main challenges for the discipline include: 1) Reducing as much as possible the dependence on fossil fuel as carrier of the energy converted into the thermodynamic separation work, in order to also reduce the emission of CO2 and other greenhouse gases. This may be achieved by approaching the thermodynamic minimum energy demand as close as possible, for example through smart integration of heat transfer operations, which may include heat pumps. Alternatively, by using a more sustainable driving force (e.g., electric driving forces powered by green electricity). 2) Becoming more flexible and able to handle streams with an increasingly complex nature, as required by the circular economy ambitions. These have a variety of origins such as in recycle- and bio-steams, and flexibly handling such complex streams that vary in composition from day to day may be addressed using modular fractionation strategies, where parts of unit operations can be switched on and off easily and without large losses. 3) Developing novel environmentally benign sorbents/solvents/etc. As an example, the development of novel natural deep-eutectic solvents to harvest valuable components from biomass-derived feedstocks can be mentioned. Another important area is the separation of delicate high value molecules such as proteins, vitamins and antibodies, which should very selectively be separated under very mild conditions to preserve their properties and value. Such surgical precision separations are applicable to a range of high-value products in food processing with an increasing focus on nutritional value, as well as in (bio) pharmaceuticals and agrochemical applications.

Process Systems Engineering (PSE)

PSE develops methodologies to support decision-making in a complex environment to optimally plan, design, operate and control chemical processes. For a truly sustainable technology the decisions should be based on economic, ecological and social implications. The boundaries of the system can be chosen differently in space (a chemical plant, an industrial complex, a company, the industry, ..) and time (tomorrow, a quarter, plant lifetime..). PSE contributions and developments in six areas are foreseen: 1) smart process modeling where the concept of artificial intelligence, coarse-graining, and digital twinning is fully used, for example also to optimize properties of solvents/catalysts etc., 2) dynamic modeling tools that can be used to evaluate and optimize processes with dynamic operation when the production capacity follows availability/price of sustainable electricity, 3) uncertainty assessment including advanced data analysis, 4) multi-criterion decision-making, 5) algorithmic solution methods that can be used to design and operate the future interconnected process systems, 6) the overall integration, the implementation, sharing and valorization of the tools via the creation of human capital.
Heat remains a very important area of attention. It represents 80% of present industrial energy use. A thorough understanding and insight in this field beyond the classical pinch is essential. This can lead to the direct use of electrical power for high temperature processes and subsequent energy extraction through power generation combined with lower temperature heating medium.
Future process automation will need to be adaptive, because of varying feedstock mixes, energy supply profiles as well as more specific and tailored demands from markets. The boundary between batch and continuous processes will blur and process automation and safeguarding will have to perform in any state the process is in. This will call for multi-level and dimensional data integration from physical equipment to anyone in need of interaction with the process with full data integrity and security. AI, VR, AR will play ever increasing roles in areas such as direct operations, training, safety, maintenance, quality and reliability.

To address these new challenges Process Technology have to connect to the following key technologies:

- Advanced materials (ST1, e.g. catalysts)
- Chemical technologies (process technology (ST5-1), Reactor engineering (ST5-2), Separation technologies (ST 5-3) and Analytical technologies (ST 5-5))
- Life sciences technologies (Biocatalysis (ST7-1))
- Nanotechnologies (nanomanufacturing (ST6-1), nanomaterials (ST6-2))

Expected results present – 2050

Scientific/technological goal:

- Versatile multi-scale modeling approaches and high-resolution measurement techniques facilitating smooth translation from lab/pilot-scale to industrial application.
- A toolbox for developing novel reactor/separator types based on alternative (sustainable) energy input (electricity, light, etc.) with optimal use of additive manufacturing, including scale-up approaches.
- New technology portfolio of separations working close to the thermodynamic limit and with renewable energy input.
- Digital twin approaches are widely available.
- AI/ML methodologies for reactor modeling, process design, control and optimization widely available.

Industrial end goal:

- Climate-neutral chemical industry while being economical with flexibility in operation: being able to deal with fluctuating electricity supply

3.2 Catalysis

Innovating Catalysis

Key to catalysis has been, and will be, to provide high activity, selectivity and stability in chemical reactions. Also in the field of biocatalysis, new developments on enzyme evolution and incorporation of newly developed enzymes into metabolic pathways pave the way to more efficient biocatalytic manufacturing. (Bio)catalysts need to convert a feedstock with a high rate to decrease reaction time and decrease energy input. (Bio)catalysts need to achieve a high selectivity to prevent additional downstream processing (separation) steps and prevent waste formation. In addition catalysts need to be stable to prevent i) need for increased energy input, ii) frequent reactor shut-down, and iii) the (bio)catalysts themselves to become waste. There will be a large need to develop (bio)catalysts for new, sustainable chemistry and these should meet all these conditions. Therefore a continued research focus will be needed on themes s.a. precise catalyst synthesis, understanding of (bio)catalytic performance and catalyst deactivation. For this tools like operando characterization and computational methods will be further developed.

New challenges can be identified for (bio)catalysis. Most notable are:

- **New feedstocks**
  With the transition towards a more sustainable society, catalytic processes for alternative feedstocks, rather than fossil-based feedstocks, need to be developed to produce chemicals, fuels, and materials. Only three renewable resources containing the carbon we need in these products are available i.e. biomass, CO_2 are recycled polymers/plastics. In the conversion of these feedstocks, new catalysts that are able to cope with these feedstocks (and their impurities!) will play a crucial role.
- **Use of alternative stimuli to drive reactions**
  With the envisioned surplus of renewable electricity, new ways of (combinations of) energy input instead of the currently applied heat, like photons, electrons, plasma, or electromagnetic waves, are expected to become more important in catalytic processing. This requires new catalysts which can deal with (combinations of) these forms of energy. Highly light-efficient semiconductors in combination with suitable, nanoparticulate “co-catalysts” to reduce energy barriers of photon-induced electron transfer reactions, potentially stimulated by heat (photothermal catalysis), need to be developed. Plasmonic

particles might allow local, light induced heating, reducing the energy input required for external heating of the reactor. To upscale photocatalytic, photoelectrochemical, or photothermal production routes, efficient reactors need to be designed, either solar exposed, or illuminated by artificial light sources. Gas-solid reactors have been proposed, which allow simultaneous introduction of heat and visible light.
Electrocatalysis can bring great opportunities for greening industrially relevant processes. Electrochemistry is of relevance for the production of hydrogen, CO_2 conversion, and perhaps production of ammonia from nitrogen and water. Improved non-noble metal catalysts need to be developed with a long lifetime which allow a high current density and Faradaic efficiency. Integration of the catalysts by advanced system design for electrochemical processing is desired.

- **Plasma catalysis**
  Plasma catalysis has recently gained traction, in particular as an alternative to Haber Bosch ammonia synthesis. The current research is mostly fundamental and little attention has been given to the technical and economic feasibility of plasma-catalytic syntheses. The technology appears most feasible for small-scale operation. Plasma catalysis potentially has a fast response to intermittent renewable electricity, and process intensification and integration with other process steps can lead to a further overall improvement.

- **New biocatalysts**
  Microorganisms and their enzymes offer a multitude of opportunities for biocatalytic manufacturing. Among the big challenges are the identification and engineering of enzymes for synthesis of chemicals and the combination of enzymes into new synthesis pathways to enable the construction of complex building blocks. Processes that combine sequential enzymatic and microbial conversions are also interesting, and could include the use of metabolic engineering.
  Microorganisms and enzymes can be exploited for the production of natural (or nature-inspired) molecules in the laboratory (and further upscaling to industrial processes). Biocatalysis in combination with electrochemistry also offers novel opportunities, e.g. microorganisms that are able to transfer/receive electrons (e.g. from electrodes) or regeneration of enzymes with bound metals. Microorganisms and enzymes involved in CO2 fixation could play an important for efficient carbon capture and utilization (CCU). Enzymes can also be of great importance in degrading natural compounds (polymers, nitrogen-and sulfur-containing compounds, etc.). They can also be used to degrade recalcitrant compounds like microplastics and micropollutants. The combination of biocatalysts and chemocatalysts needs to be considered as well for the production of the needed products.

- **Use of well abundant catalytic materials**
  Traditionally, when designing and developing catalysts with high performance, material restrictions have not been taken into consideration as much as is required by elemental scarcity nowadays. With the increasing scarcity of noble elements, alternative elements need to be found to construct catalytic functionality. Besides innovative screening methodology, computational chemistry has become an important tool in studying the mechanistic pathways of chemical reactions. DFT calculations provide additional insight in optimizing chemical transformations improving the predictability of both the stereoselective outcome of reactions and reactivity of catalysts.

- **Use of computational approaches and AI**
  Artificial intelligence (AI) may be of great help in the retrosynthetic analysis of functional molecules. Although search engines for finding specific transformations in the scientific and patent literature have matured, computer-aided retrosynthetic analysis is still, despite intensive efforts in several labs since the eighties of last century, in its infancy. Furthermore, analytical tools such as in situ (or online) IR, NMR and mass spectrometry, with or without connection to UPLC or HPLC equipment, will speed up methodology development. Besides gaining quick and precise structure information, such analytical tools also facilitate the study of reaction kinetics and thermodynamics. AI/Machine Learning (ML) will also accelerate and structure process R&D in 'Making Molecules'.

- **Use of non-toxic and abundant metals**
  Future catalysts should be based on non-toxic and abundant metals. Due to rapidly evolving fields of bio- informatics, structural biology and genome editing, tailor-made enzymes can be made to enable selective transformation in non-natural molecules and even catalyze non-natural reactions. The current border between hetero- and homogeneous catalysis that is mainly characterized by the fact the former reactions are carried out in continuous processes and the latter in batch will be faded by flow chemistry. In addition, flow chemistry is highly promising because of the simplicity of upscaling from lab to production scale of the multistep synthesis of complex functional molecules.

- **Integration of multiple catalysts and multiple stimuli**
  Often catalysts are designed for a specific conversion. Products are purified and further converted when needed. It would be more efficient when the number of processing steps could be decreased, and catalytic steps can be integrated. That requires new robust catalysts and an integration of the catalysts with the downstream processes. In other words, we need catalysts and reactors which enable process intensification, in particular when multiple stimuli need to be introduced.

To enable a more efficient and sustainable manufacturing of functional molecules it is important to fully exploit the complementarity of synthesis and catalysis aiming at increasing the selectivity of synthetic transformations and expanding the reaction scope of biocatalysis. In addition, in the next decades the feedstock for the synthesis of functional molecules will shift from fossil to renewable sources such as agricultural products but also from CO2 reduction and follow up homologation. Therefore, novel methodologies have to be developed to cope with these green challenges. As a result, in the next decades synthetic chemists will not only be able to design and make even more complex molecules with advanced properties but also manufacture them in a sustainable fashion from biobased materials. With the help of advanced analytical techniques, a deeper insight will be gained in "how molecules react" and this will be beneficial for various fields and provide sustainably manufactured highly effective molecules for biology, medicine and material applications.

To address these new challenges catalysts have to connect to the following key technologies:

- Advanced materials (ST1, e.g. catalysts)
- Artificial intelligence (AI) (ST4-1)
- Chemical technologies (Process technology (ST5-1), Reactor engineering (ST5-2), Separation technologies (ST 5-3) and Analytical technologies (ST 5-5))
- Nanotechnologies (nanomanufacturing (ST6-1), nanomaterials (ST6-2))
- Life sciences technologies (Biocatalysis (ST7-1))
- Engineering and fabrication technologies (Additive manufacturing (ST8-4))

Expected results present – 2050

Scientific/technological goal:

- Taylor designed sustainable (collaborative) catalysts, allowing application of multiple reaction stimuli
- Catalysts are based on non scarce materials where possible
- Understanding of catalytic processes a.o. by (operando) characterization and/or computational methods
- New processes where biocatalysts and chemical catalysts are combined in a synergistic fashion

Industrial end goal:

- Catalytic processes for circularity i.e., able to convert renewable feedstocks (biomass, CO_2, recycled polymers/plastics)
- Catalytic processes avoiding CO_2 formation
- Stable and efficient biocatalytic processes to produce natural or nature-inspired molecules (difficult to produce chemically)
- Robust catalytic systems based on abundant metals
- Precise catalyst synthesis (active phase, texture, shaping)

Bijlage A: Chemical Key technologies (Sleuteltechnologieën)[1]

ST 1: Advanced Materials
ST1-1 Energy Materials
ST1-2 Optical, electronic, magnetic and nanomechanical materials
ST1-3 Meta materials
ST1-4 Soft/bio materials
ST1-5 Thin films and coatings
ST1-6 Construction and structural materials
ST1-7 Smart materials
ST1-8 Circular materials and recycling technologies

ST 2: Photonics and optical technologies
ST2-1 Photovoltaics
ST2-2 Optical systems and integrated photonics ST2-3 Photonic/optical detection and processing
ST2-4 Photon generation technologies

ST 3: Quantum technologies
ST3-1 Quantum computing
ST3-2 Quantum communication
ST3-3 Quantum Sensing

ST 4: Digital and information technologies
ST4-1 Artificial intelligence (AI)
ST4-2 Data science, data analytics and data spaces
ST4-3 Cybersecurity technologies
ST4-4 Software technologies and computing
ST4-5 Digital connectivity technologies
ST4-6 Digital Twinning and Immersive technologies
ST4-7 Neuromorphic technologies

ST 5: Chemical technologies
ST5-1 Process technology; including process intensitifaction
ST5-2 (advanced) Reactor engineering
ST5-3 Separation technology
ST5-4 Catalysis
ST5-5 Analytical technologies
ST5-6 Electricity-driven chemical reaction technologies

ST 6: Nanotechnology
ST6-1 Nanomanufacturing
ST6-2 Nanomaterials
ST6-3 Functional devices and structures (on nanoscale)
ST6-4 Micro- and nanofluidics
ST6-5 Nanobiotechnology/bionanotechnology

ST 7: Life science technologies ST7-1 Bio-catalysis
ST7-1 Biomolecular and cell technologies
ST7-2 Biosystems and organoids
ST7-3 Biomanufacturing and bioprocessing
ST7-4 Bio-informatics

ST 8: Engineering and fabrication technologies
ST8-1 Sensor and actuator technologies
ST8-2 Imaging technologies
ST8-3 Mechatronics and Optomechatronics
ST8-4 Additive manufacturing
ST8-5 Robotics
ST8-6 Digital manufacturing technologies
ST8-7 Semiconductor technologies
ST8-8 Systems engineer

Credits

The contents related to circular critical and finite materials in the theme-oriented chapter 2.2 ‘Making molecules circularly’ was contributed by Susanne van Berkum (TNO) and Douwe Huijtema (KIA-CE)