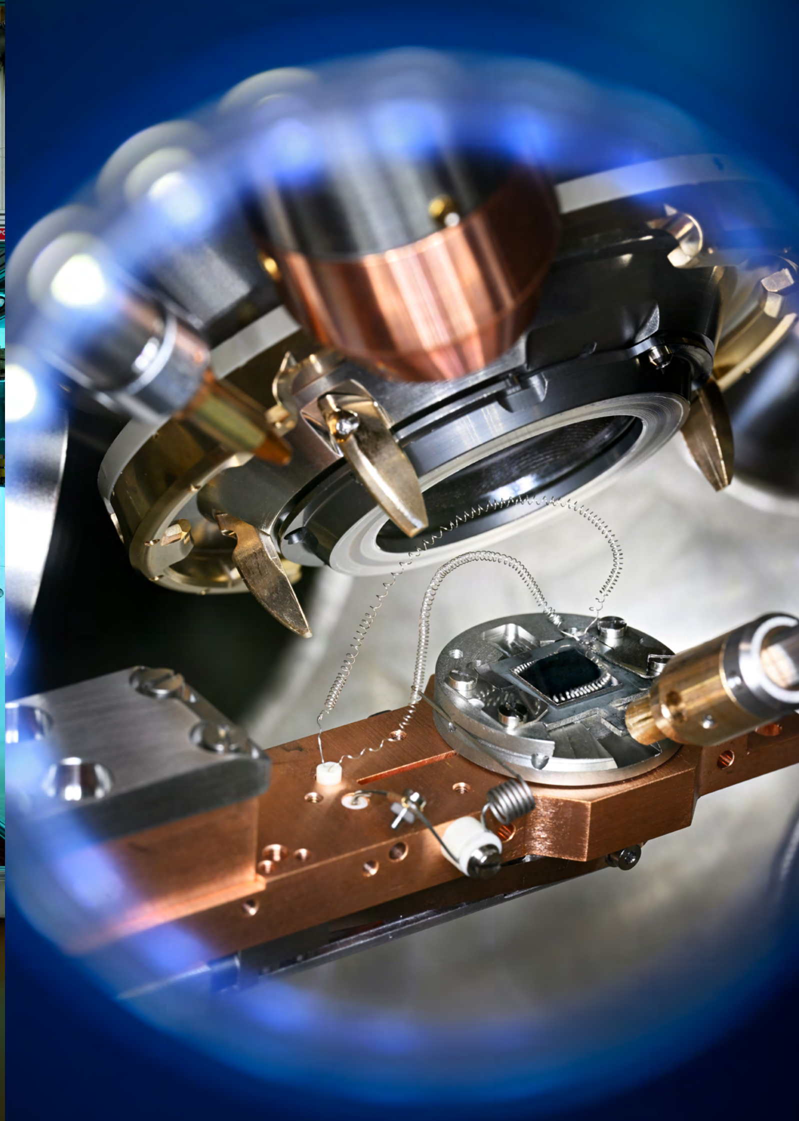

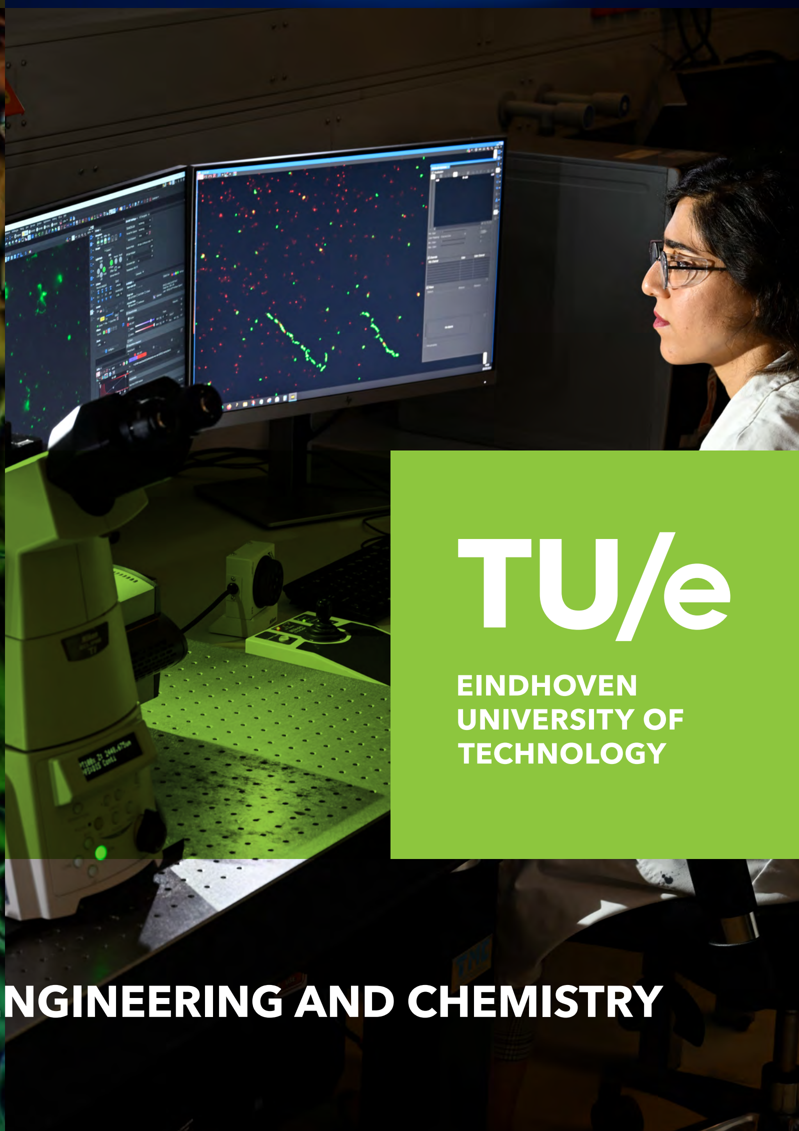

Research self-assessment 2015-2021

TU/e
EINDHOVEN UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF CHEMICAL ENGINEERING AND CHEMISTRY

Cover photo top left: Electrolyzer setup to produce hydrogen efficiently and at a high intensity.

Cover photo top right: Near-ambient pressure X-ray photoelectron spectroscopy equipment to study the composition and oxidation state of the outermost layers of catalysts during a chemical reaction.

Cover photo bottom left: Liquid crystal artwork: polarized optical microscope image of a typical liquid crystal in its nematic phase.

Cover photo bottom right: Super-resolution microscope to study the density and distribution of active sites within a polymer coating of microparticles.

This report has been printed on fully recycled paper.

Research self-assessment 2015-2021

EINDHOVEN UNIVERSITY OF TECHNOLOGY

DEPARTMENT OF CHEMICAL ENGINEERING AND CHEMISTRY

Preface

This is the research self-assessment report of the department of Chemical Engineering and Chemistry, one of the nine departments of Eindhoven University of Technology, the Netherlands. It has been written as part of the national evaluation to assess research units in light of their own aims and strategies, following the Strategy Evaluation Protocol (SEP) for 2021-2027 established by Universities of the Netherlands (UNL), the Dutch Research Council (NWO) and the Royal Netherlands Academy of Arts and Sciences (KNAW). It is used to evaluate the research quality, societal relevance and viability of research in public institutions in the Netherlands in a six-year cycle.

This report starts with an introduction to the department (Chapter 1) describing its mission and research, the organizational structure and embedding, and its infrastructural and financial position. Chapter 2 subsequently provides the main strategic aims for the evaluation period (2015-2021), while the strategy followed to achieve these aims is discussed in Chapter 3. In the next chapter, Chapter 4, major external factors that occurred during the review period are briefly addressed in the context of the department's achievements during the review period. Chapter 5 then presents and explains the factual evidence and achievements related to the quality of the research and societal relevance in view of the strategic aims. This part is complemented with quantitative indicators and narrative descriptions, as well as several case studies. To conclude this research self-assessment report, Chapter 6 reflects on the department's ambitions and strategy for the future. An additional booklet describing the research groups of the department in more detail complements this research self-assessment report.

This research self-assessment report is a joint effort by all of the people in the department: those who contributed to the discussions and the writing while making this report but especially all of our students, researchers and scientific and support staff. The ambitions, achievements and contributions described in this report are the result of their commitment and dedication to the department's research and education in chemical engineering and chemistry, making the department well-positioned for the future. We are proud on what we have accomplished together.

We hope you will enjoy reading this report and we look forward meeting you in person to discuss our achievements of the past and ambitions for the future.

On behalf of the department of Chemical Engineering and Chemistry,
Prof.dr.ir. Kitty Nijmeijer (dean), Prof.dr.ir. Emiel Hensen (vice-dean),
Prof.dr.ir. Remco Tuinier (vice-dean), Dr. Mark de Graef (managing director)
September 2022

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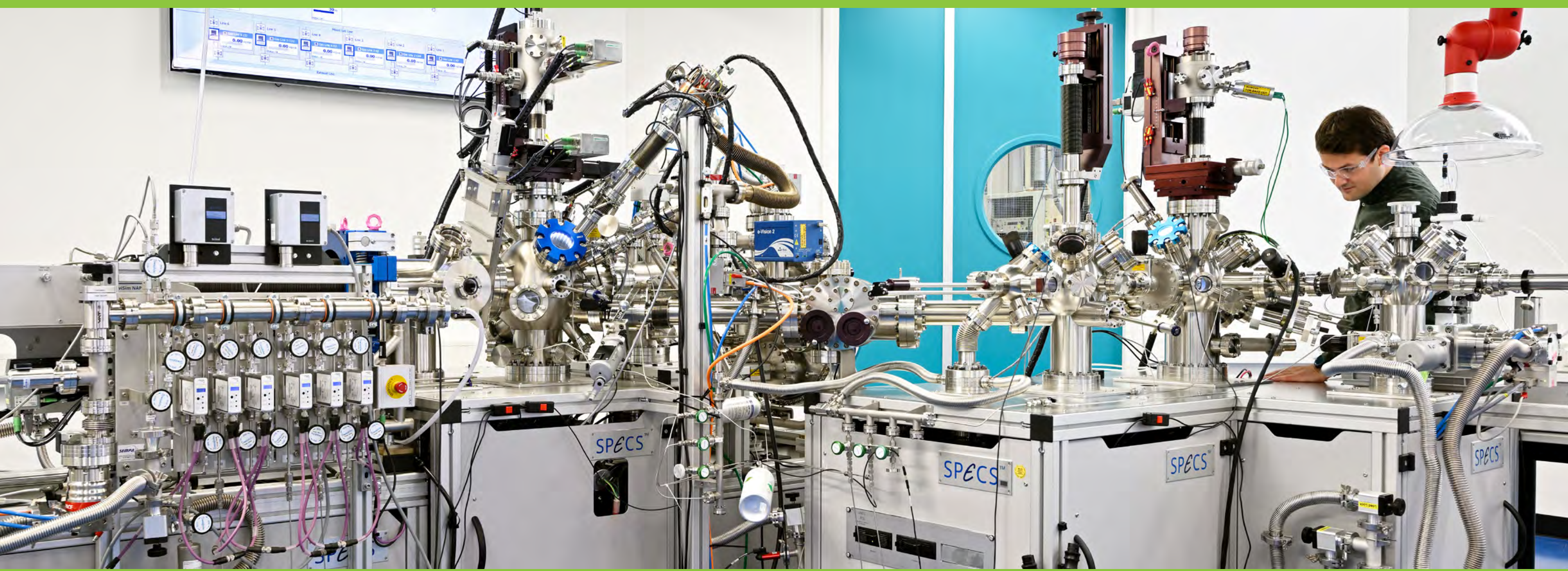
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1. Introduction

1.1. MISSION OF THE DEPARTMENT

The Department of Chemical Engineering and Chemistry is a nationally and internationally valued department of Eindhoven University of Technology (TU/e). The mission of the department is to be a center of inspired learning in chemical engineering and chemistry, encouraging the pursuit of new knowledge and innovative scholarship. To fulfill this mission, its vision is to provide strong chemical engineering and chemistry education on solving complex societal problems to advance basic science and technology while impacting the chemical industry, other associated industries and broader society. By interlinking molecular systems, materials chemistry and chemical engineering sciences, the department bridges fundamental research and marketable applications and commits itself to excellence in education, research and valorization.

1.2. SCIENCE AND EDUCATION

Very recent global developments clearly stress the importance of science and technology in solving societal problems. Scientists in the department feel an urgent responsibility to contribute to solving the challenges of today and the future related to energy supply, resource scarcity and health. This is done in close collaboration with other knowledge institutes, industrial partners and societal organizations to ensure industrial and societal relevance. Research and education are strongly intertwined in our department. Most of the department is located in the Helix building on the TU/e Science Campus and houses a modern lab infrastructure with a wide range of advanced scientific instruments and facilities for educational and research activities.

The department has a collegial atmosphere with multiple collaborations and the sharing of expertise and scientific equipment infrastructure, unrestricted by organizational boundaries. To create scientific strength, visibility and coherence, research in the department is currently organized into two thematic research domains: 1) Molecular Systems and Materials Chemistry, covering research involving atomic-scale molecular design and the nanoscale organization of new functional materials, and 2) Chemical and Process Technology, focusing on the design of integrated multiphase reactors, process engineering and equipment concepts. The researchers in the department perform cutting-edge research in chemical engineering and chemistry at the forefront of science and technology, covering the knowledge chain ranging from molecules to processes.

Molecular Systems and Materials Chemistry
The Molecular Systems and Materials Chemistry domain focuses on the design, synthesis and dedicated molecular engineering of novel molecules, macro and supramolecular assemblies, and functional, responsive or bio-inspired materials. Researchers in this cluster investigate how to control the chemistry, structure and morphology of materials and interfacial phenomena at different length scales of polymers and supramolecular constructs and relate the material features to the functional performance of such advanced and interactive materials. Moreover, this involves new routes to polymer materials using renewable resources and polymer recycling.

This domain involves the following research groups:

- Bio-Organic Chemistry
- Macro-Organic Chemistry
- Molecular Materials and Nanosystems
- Physical Chemistry
- Polymer Performance Materials
- Self-Organizing Soft Matter
- Stimuli-responsive Functional Materials and Devices
- Supramolecular Chemistry and Catalysis
- Supramolecular Polymer Chemistry

Chemical and Process Technology

This domain performs research in the field of chemical engineering sciences, ranging from a fundamental scientific understanding of chemical conversion processes to targeted engineering applications and industrial innovation. Research focuses on the design, development and innovation of integrated and intensified reactors, separation technology, process intensification, and molecular heterogeneous catalysis across the relevant length scales through experimental and modeling activities. There is a strong emphasis on biobased and, more recently, electrochemical conversion to fuels and chemicals and energy storage processes.

The Chemical and Process Technology domain involves the following research groups:

- Chemical Process Intensification
- Inorganic Materials and Catalysis
- Membrane Materials and Processes
- Multi-Scale Modeling of Multiphase Flows
- Sustainable Process Engineering

A detailed overview of the different research groups in the department, including their research expertise, research facilities, prospects and key publications, can be found in the additional booklet attached to this report.

To position the department, Table 1 provides an overview of the scientific expertise on molecules, materials and processes of the research groups listed above and correlates this to the societal challenges that we focus on.

Table 1: Overview of scientific expertise on molecules, materials and processes and contribution to the societal challenges of the research groups.

Research group	**Scientific expertise**			**Societal challenges**		
Molecular Systems and Materials Chemistry	***Molecules***	***Materials***	***Processes***	***Energy***	***Circularity***	***Health***
Bio-Organic Chemistry	•	•				•
Macro-Organic Chemistry	•	•				
Molecular Materials and Nanosystems	•	•		•		
Physical Chemistry	•	•		•	•	•
Polymer Performance Materials	•	•			•	
Self-Organizing Soft Matter	•	•			•	•
Stimuli-responsive Functional Materials and Devices	•	•		•	•	•
Supramolecular Chemistry and Catalysis	•	•			•	•
Supramolecular Polymer Chemistry	•	•			•	
Chemical and Process Technology						
Chemical Process Intensification			•	•	•	
Inorganic Materials and Catalysis	•	•	•	•	•	
Membrane Materials and Processes	•	•	•	•	•	
Multi-Scale Modeling of Multiphase Flows			•	•	•	
Sustainable Process Engineering		•	•	•	•	

The above overview emphasizes the areas of gravity in the department regarding molecules and materials for health and materials and processes for energy applications. The earlier-acquired Gravitation program (Dutch Research Council; NWO) entitled Functional Molecular Systems (2013-2023) and the very recently granted program entitled Interactive Polymeric Materials Research Center (2022-2032) confirm the scientific and innovative strength of polymer science and technology at the department and TU/e. The Gravitation program Netherlands Center for Multiscale Catalytic Energy Conversion (2014-2024) acknowledges the quality of the department regarding catalytic processes and energy conversion.

1.3. ORGANIZATION OF RESEARCH GROUPS

All academic staff members in the department are embedded in research groups of 2-5 people who share responsibilities in education and research within a specific scientific area. The permanent staffing of such a research group typically consists of a chair with one or more professors and associate professors, one or more (tenure-track) assistant professors and several technical support staff members. All staff members are scientifically independent and everyone is encouraged to develop his/her own independent line of research. We give room to everyone's talent, also allowing younger scientific staff to carry responsibility and take leadership early on in their careers depending on individual career paths and track records in research, education and valorization. More experienced scientific staff have a clear responsibility to coach and stimulate younger members in their research groups. Details on the composition of each research group are given in the additional booklet attached to this report.

1.4. POSITIONING

Table 2 summarizes the number of research staff and researchers of the department. It shows a very stable and steady number of scientific staff and PhD students over the past seven years. At the end of the review period (2021), the scientific staff of the department totals 35.2 FTE (full-time equivalent): 15.3 FTE full professors and part-time professors from industry and research institutes, 4.0 FTE associate professors, 15.9 FTE assistant professors, 24.8 FTE technical staff and 24.7 FTE support staff. There are 353 bachelor's and 270 master's students, 216.4 FTE PhD students, 45.3 FTE professional doctorate trainees and 44.9 FTE postdoctoral fellows. The department's total annual budget in 2021 was €31.6 M.

Table 2: Research staff of the department from 2015 to 2021.

FTE[1]	2015	2016	2017	2018	2019	2020	2021
Full prof.	15.2	13.3	13.0	14.1	14.7	15.8	15.3
Associate prof.	7.5	8.6	8.3	7.0	5.7	4.7	4.0
Assistant prof.	15.4	13.0	12.8	12.6	16.2	16.4	15.9
Total prof.	*38.1*	*34.9*	*34.1*	*33.7*	*36.6*	*36.9*	*35.2*
Postdocs	48.8	50.7	49.6	53.9	52.0	51.4	44.9
PhD students[2]	200.3	191.5	204.1	205.6	204.8	211.3	216.4
Total research staff	**287.2**	**277.1**	**287.8**	**293.2**	**293.4**	**299.6**	**296.5**

1 Full-time equivalent, i.e., total time of appointment; available for research, education and organizational tasks
2 PhD students, including both fully employed by the department and externally or internally funded but not employed by the department

Many researchers of the department are actively involved in interdisciplinary TU/e research at the Institute for Complex Molecular Systems (ICMS) and the Eindhoven Institute for Renewable Energy Systems (EIRES).[1] Prof. Bert Meijer of the department is the founding director of ICMS, while Prof. Emiel Hensen was closely involved in the creation of EIRES. Besides enhancing multidisciplinary research in collaboration with industry, the institutes also coordinate e.g., TU/e involvement in the definition of external research programs or the writing of large research grants applications. The involvement of many researchers of the department in the definition of several joint National Growth Fund[2] proposals on 'Self-thinking molecular systems', 'Sustainable materials NL', 'Green hydrogen (Groenvermogen)' and 'Alkaline electrolysers' are examples of this. Strong collaborative ties exist with the Departments of Biomedical Technology (BMT) and Applied Physics (AP) regarding, amongst other things, shared professorships between the two departments, joint research projects and the sharing of equipment, infrastructure and laboratories.

Apart from collaboration within TU/e, the department puts much effort into collaboration with other universities and universities of applied science at the level of individual (groups of) researchers and in strategic knowledge alliances with, for example, Utrecht University, Wageningen University and University Medical Center Utrecht. Together with the Technical University of Denmark (DTU), the Swiss Federal Institute of Technology Lausanne (EPFL), the Technical University of Munich (TUM), Technion and the Institute Polytechnique de Paris, TU/e is a partner to the EuroTech Universities Alliance, a strategic partnership of leading European universities of science and technology that collectively aim for first-class research, education and innovation through the sharing of curricula, PhD research exchanges and flagship projects, such as the EuroTechPostdoc program, the European Venture program and the EuroTeQ Engineering University program. The researchers of the department also collaborate extensively with national and international universities, universities of applied sciences, research institutes and industries in public-private partnerships and bilateral collaborations. Examples include strategic partnerships such as Chemelot InSciTe, the Institute for Sustainable Process Technology (ISPT), the Dutch Polymer Institute (DPI), the Materials Innovation Institute (M2i), NanoNextNL, CatchBio and the Advanced Research Center Chemical Building Blocks Consortium (ARC

1 The cross-disciplinary research institutes of TU/e combine the scientific and technological strengths of the researchers in the departments of the university with industrial needs. TU/e has four research institutes: the Eindhoven Artificial Intelligence Systems Institute (EAISI), the Eindhoven Institute for Renewable Energy Systems (EIRES), the Institute for Complex Molecular Systems (ICMS) and the Eindhoven Hendrik Casimir Institute (EHCI).
2 The National Growth Fund is an initiative of the Ministries of Economic Affairs and Climate Policy and Finance, providing €20 billion for large-scale investment projects and programs lead by industry. Projects and programs must contribute to the sustainable earning power of the Netherlands. https://www.nationaalgroeifonds.nl/over-het-nationaal-groeifonds

CBBC), collaborations in joint projects of the Dutch Research Council (NWO) or the EU, or bilateral projects with a broad range of companies in e.g., the chemical, biomedical, food, pharma, water and metallurgical industries.

1.5. ORGANIZATION OF THE DEPARTMENT

The organizational structure of the department is presented in Figure 1.

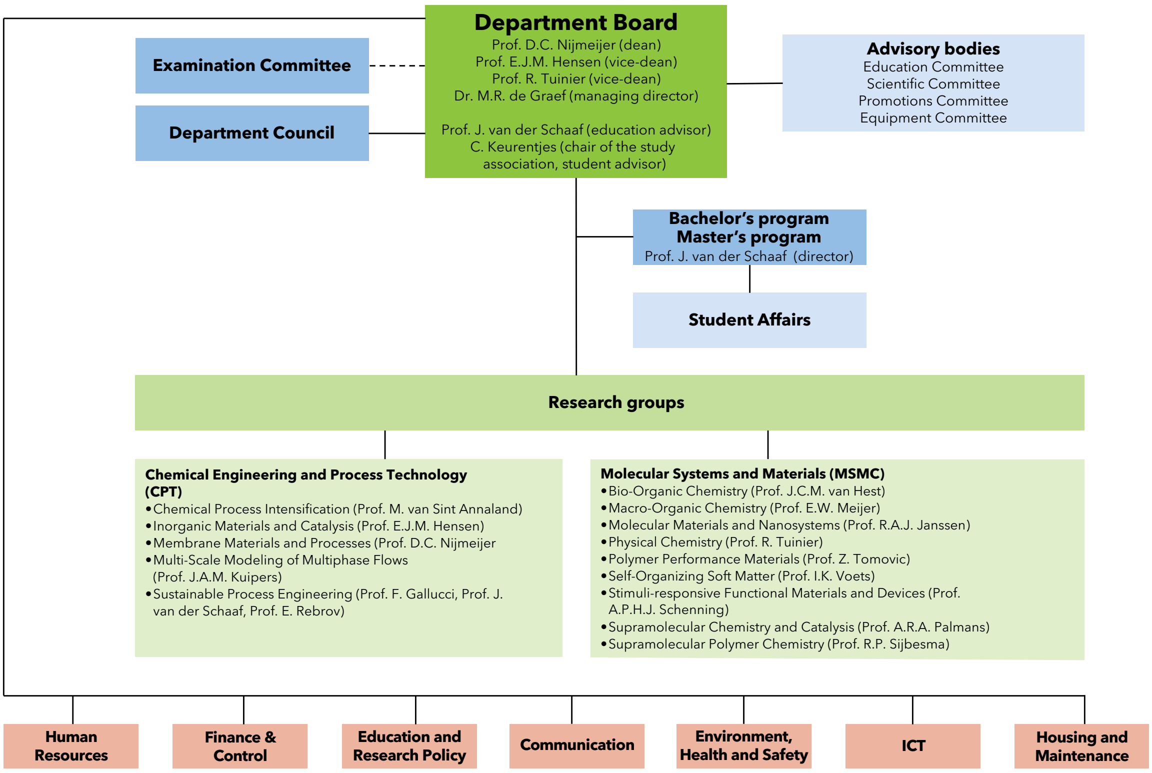


Figure 1: Organogram of the department.

The *Department Board* is appointed by the Executive Board of TU/e, consists of a dean, 1-2 vice-dean(s) and a managing director and manages all aspects of the department's business. The *dean* leads and represents the department. He/she is responsible for all aspects of the department's operations, including strategy, finance, appointments of assistant professors, proposals for appointments of associate and professors, education (together with the *director of education*), staff and quality assurance. The *research groups* have a direct link with the Department Board without any intermediate administrative layer. The *Council of Full Professors* is the assembly of all full professors, which meets monthly to discuss strategic and managerial matters. Also, there are frequent meetings of the Department Board with all scientific staff on specific strategic topics. Every ~1.5 years, the department organizes its *research and education days*, reflecting on the current status and future directions of education and research. The Department Board has regular meetings with the *Department Council* (participatory body for students and staff in the department; active role in assessing the annual budget and major organizational and/or educational changes proposed by the Department Board), the *Science Committee* (advises on all strategic issues related to the departmental research program in the broadest sense, including the profiles of new scientific staff members), the *Promotions Committee* (advises on promotions of internal scientific staff members and intended appointments of external scientific staff members and all issues related to the career development of scientific staff, including research staff policies and the individual careers of staff members) and the *PhD Council* (advises on PhD-specific aspects).

1.6. INFRASTRUCTURE

The department is housed in the Helix building on the TU/e Campus. The Helix building was constructed in 1998 and was scheduled to be renovated in 2025. Due to changing priorities, this has now been delayed to after 2030. To address the most critical aspects (ventilation, heating system, etc.), €10 M has been reserved to keep the building's operations running until its renovation. As the building is almost 25 years old, maintenance costs are significant and the relatively old infrastructural facilities of the building are not always in line with the requirements for the installation of new, state-of-the-art equipment.

The department hosts an impressive range of state-of-the-art scientific equipment, instruments and facilities within the different expertise areas, which enables it to perform its educational and research activities. The basic experimental equipment is up to date, though in some cases reaching the end of its lifetime. All research groups have dedicated equipment specialized for the specific fields of expertise of the respective groups. In addition, the Center for Multiscale Electron Microscopy (CMEM) very recently acquired, with the strong support of DAF Trucks/the PACCAR Foundation, an advanced electron microscope for high-resolution visualization and analysis of materials at the smallest scale. Moreover, it operates (cryo-)TEM and three (FIB-)SEM microscopes. The department also hosts modern liquid and solid-state NMR spectrometers with in-situ/operando capabilities, among other things. A unique in-situ MRI facility for the characterization of hydrodynamic processes in chemical reactors was also established during

the review period. For surface characterization, advanced X-ray photoelectron spectroscopy infrastructure is available, including a near-ambient pressure XPS apparatus. Researchers also have access to other extensive unique research infrastructure in other departments and in the research institutes, including the cleanroom facilities at NanoLab@TU/e, the manufacturing facilities at the MicroFab Lab and the advanced imaging and spectroscopy facilities of the ICMS. Specialized equipment is designed and constructed by the Equipment & Prototype Center at TU/e.

Investments by the department in new apparatus and on keeping the quality of the equipment up to date are generally funded through external research grants (such as NWO Groot, ARC CBBC, Gravitation programs, ADEM, NanoNed and NanoNextNL). Only with these grants can the department maintain its state-of-the-art equipment at a high, internationally-competitive level, despite the fact that resources for standard, basic but essential equipment are limited.

1.7. FINANCIAL RESOURCES

The department uses direct university funding for the salaries of permanent research staff, educational and support staff and the department's exploitation costs of housing. The running costs for research projects, including the salaries of temporary research staff (PhD students and postdoctoral research fellows), bench fees, consumables and capital investment in research infrastructure are covered by external funding. This external funding encompasses research grants and funding from contract research.[3]

Table 3 summarizes the funding and expenditures at the department level in the review period. Despite the relatively small size of the department and the limited direct university funding, the financial situation of the department is very strong, with funding from research grants (fundamental research based on scientific excellence) and contract research (practical applications in collaboration with private partners) amounting to nearly twice the size of the direct university (fixed costs) funding. This high level of external funding relative to the small size of the department is evidence of the quality and quantity of the research, with a significant impact on science, industry and society. This is only possible thanks to the commitment of the people in the department combined with the strong acquisition of external research funding and efficient and effective use of it.

Table 3: Funding and expenditures at the department level in the review period (shown as millions of euros, including funding and costs for non-research staff, like educational and support staff).

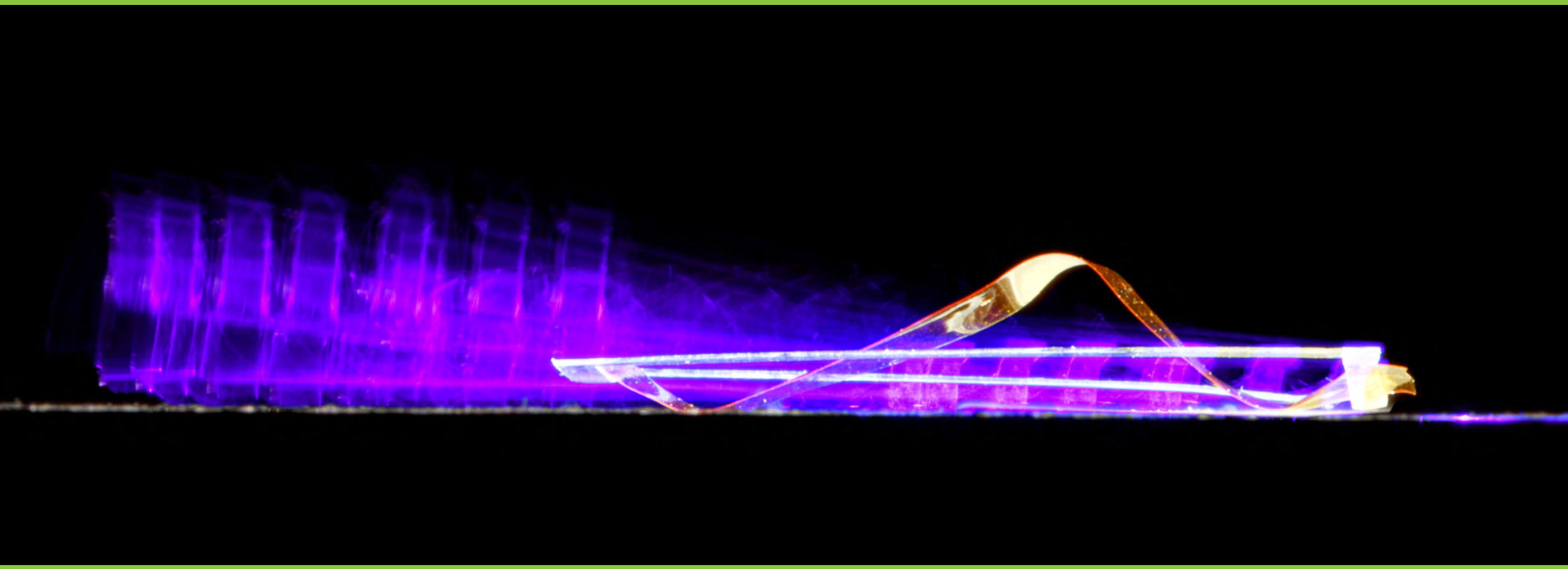
Year	2015		2016		2017		2018		2019		2020		2021	
Research funding	***€ M***	***%***	***€ M***	***%***	***€ M***	***%***	***€ M***	***%***	***€ M***	***%***	***€ M***	***%***	***€ M***	***%***
Direct funding[1]	11.513	44	11.175	41	12.212	42	13.101	44	14.899	47	14.474	46	15.558	49
Research grants[2]	3.236	12	3.876	14	5.528	19	5.137	17	4.865	15	5.009	16	4.210	13
Contract research[3]	11.371	44	12.167	45	11.642	40	11.537	39	11.954	38	12.157	38	11.834	37
Total funding	**26.120**		**27.219**		**29.382**		**29.776**		**31.718**		**31.640**		**31.602**	
Expenditure	***€ M***	***%***	***€ M***	***%***	***€ M***	***%***	***€ M***	***%***	***€ M***	***%***	***€ M***	***%***	***€ M***	***%***
Personnel costs	19.585	75	20.247	74	21.388	72	22.305	75	23.722	74	23.324	73	23.628	74
Other costs	6.526	25	7.145	26	8.289	28	7.547	25	8.186	26	8.499	27	8.242	26
Total expenditure	**26.110**		**27.392**		**29.676**		**29.853**		**31.908**		**31.823**		**31.870**	

[3] University funding in the Netherlands consists of:

[1] Direct funding from the government (lump-sum budget)

[2] Research grants obtained in national scientific competition from e.g., the Dutch Research Council (NWO) and the Royal Netherlands Academy of Arts and Sciences (KNAW)

[3] Contract research on specific research projects obtained from external organizations, such as industry, government ministries, European organizations and charity organizations (e.g., EU projects, industry grants and grants from public-private partnerships)



2. Strategic aims

2.1. MAIN STRATEGIC AIMS FOR THE REVIEW PERIOD

To realize our mission, as formulated in the introduction to this report, the department's strategic aims are based on three key pillars:

People

The people that we employ and educate in our department are the most important aspect. This refers to students (bachelor's/master's/professional doctorates/PhD students) and departmental and support staff. We want to provide an inclusive environment where all students, researchers and scientific and support staff can flourish and develop their talents while contributing to the shared mission of the department. The department provides an open environment with a growth mindset, with room for everyone's talent and where people learn, explore and develop their talents. This requires an open and collegial atmosphere with ample opportunity for collaboration and the sharing of knowledge and infrastructure. Attention to career development and transparent discussions on expectations regarding selection and promotion should be an integral part of this culture. This requires individual, tailor-made approaches in terms of supervision, training and HR support that best align with individual demands and wishes within a central framework of solid HR policies.

Science

We aim to perform top-notch research with state-of-the-art equipment at the forefront of science and technology in the selected areas of materials chemistry, molecular systems and chemical engineering sciences. We commit ourselves to excellence in scientific and applied research and bridge fundamental sciences with societal relevance. An important strength of the department is the chain of knowledge over many length scales linking molecular properties to macroscopic phenomena with respect to materials and chemical conversion processes in the two research domains of Molecular Systems & Materials Chemistry and Chemical & Process Technology. The education provided has a solid scientific foundation and new scientific insights and developments are naturally integrated into the educational programs.

To maintain scientific excellence and an internationally leading position at the forefront of research, we aim to reinforce our focus and mass in core research themes by retaining existing staff and hiring talented new staff. Investments in talent should build on and strengthen existing expertise in a complementary fashion, focusing on supramolecular and polymer chemistry, physical chemistry, separation technology, inorganic materials, and catalysis and chemical reactor engineering. Given the growing importance of and strong societal need for renewable energy in the form of electricity, the recommendation is to actively strengthen the department's chain of knowledge in the field of electrochemical energy conversion and storage. Digital technology is of strongly increasing societal importance and its impact in the chemical industry will grow. Technologies such as Internet of Things, artificial intelligence in combination with online/inline sensing, will also find application in the chemical industry. This topic requires attention in the coming years.

Excellence in science requires research with state-of-the-art equipment at the forefront of science and technology. The department should develop a view on selecting appropriate advanced research equipment and computational infrastructure that is relevant to the main research lines and provide matching budget. This should also include the demands for data storage and processing associated with time-resolved and 3D analysis and with current open access policies. The advice is to re-install the Equipment Committee in order to develop a strategic plan with respect to research infrastructure, including basic equipment in the department.

Societal relevance

A number of upcoming external and internal changes affect the department. Society is changing rapidly, driven by economic, technological and environmental megatrends such as globalization, climate change, the associated energy transition, the transition to a fully circular economy, health, resources and digitalization. The growing role of multidisciplinary research across the molecular up to the macroscopic length scales is evident in solving today's increasingly complex problems in the above-mentioned context.

The disciplines of chemical engineering and chemistry are of pivotal importance to the Dutch economy. Our department can specifically address these challenges, exploiting our integrated approach by combining materials chemistry, molecular systems and chemical engineering sciences. ChemistryNL is one of nine top sectors in the Netherlands, aimed at creating opportunities from global societal challenges in the areas of climate, energy, circularity and health in a sustainable manner. Against this background, the department recognizes that its primary role is to educate young professional talents that can address these and future societal challenges by offering a coherent educational program based on excellent and innovative scientific and technological research.

2.2. RESPONSE TO THE RECOMMENDATIONS OF THE PREVIOUS ASSESSMENT

Research evaluations at the level of the department take place every six years. Below, we follow up on the recommendations mentioned in the department's previous assessment in 2015.[4] Specific evidence and accomplishments are given in the next part of this report. Unlike the current evaluation, the previous evaluation was a joint evaluation of the three technical universities in the Netherlands (3TU evaluation of Chemical Engineering at TU/e, University of Twente and TU Delft).

- **Decline in direct university funding, resulting in a higher workload of staff:** In recent years, the direct funding situation of the department has improved due to a redistribution of the university funding. This has, to some degree, relieved the pressure on staff members. At the end of the current evaluation period, direct funding covered nearly all costs for permanent staff, education and general operations. For the coming years, the sector plans[5] provide additional funding for newly attracted staff members in key research areas. The acquisition of external funding remains very competitive though, implying that staff are forced to put substantial effort into grant applications.
- **Career prospects for non-tenured/tenured staff:** Following a change in Dutch law on higher education, associate professors now also have *ius promovendi*, which aligns with the notion that associate professors develop independent research lines within the university. Expectations on career prospects and promotion have been clarified, while procedures have been streamlined in such a way that the Department Board is more closely involved in the career paths of younger staff members, including through direct discussions between staff members and the board.
- **Gender balance:** During the review period, the department has striven to broadly increase the number of female staff members, specifically the number of female full professors who can act as role models. Besides this, the department hired several female tenure-track assistant professors in the recent sector plan round. Dedicated search committees are regularly tasked to identify female talent for specific positions. As presented in more detail in Chapter 5, the number of female scientific staff increased from 15 to 26% during the review period.
- **Time to doctoral degree:** A new online system to monitor the progress of PhD projects and homogenize procedures with respect to the defense trajectory has been implemented. The time between the finalization of the thesis and the actual defense remains about the same (ca. 3.5 months, see Chapter 5).
- **Ensure broad funding covering fundamental and applied research:** During the evaluation period, most of the research of the department was funded by a balanced mix of curiosity-driven fundamental research on the one hand and more applied research on the other. This holds not only for the many relatively small projects but also for larger consortia covering fundamental research and applied research.
- **Visibility of young researchers on the TU/e website:** The TU/e website has been redesigned and all researchers have their own research pages in line with the policy that all staff, including junior staff, develop their own research lines.

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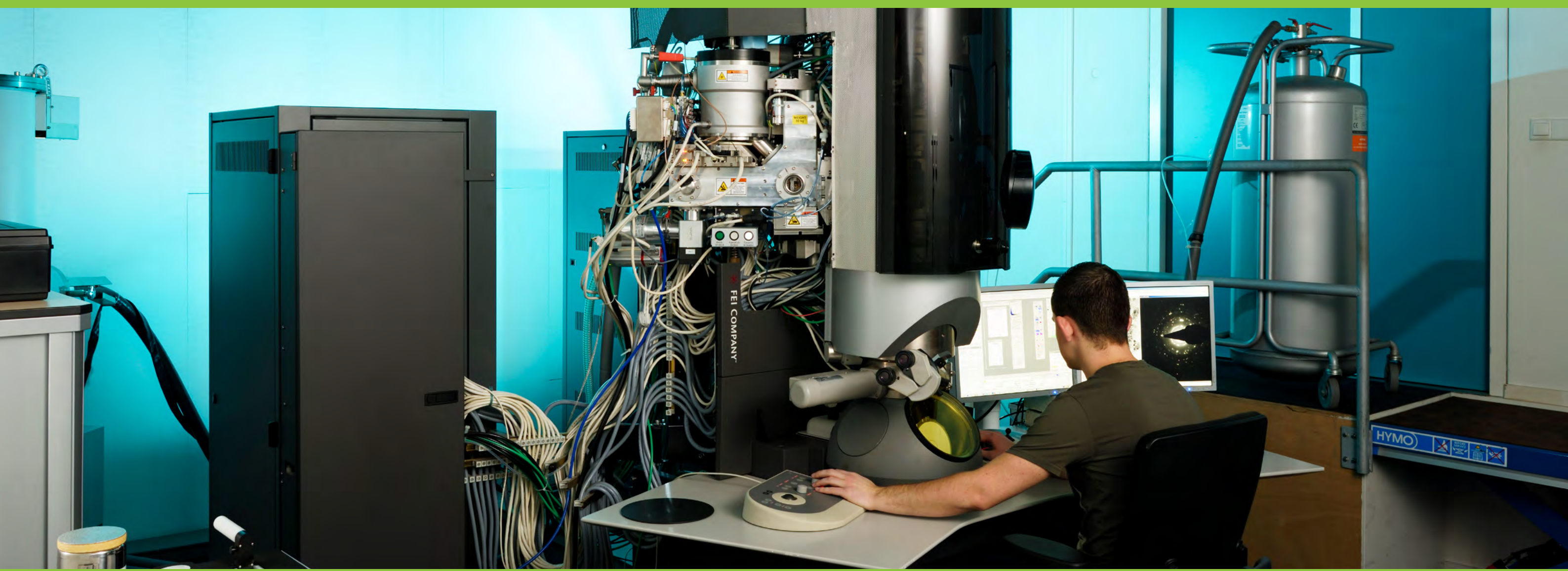
4 The assessment report of the 3TU evaluation (2010-2015) is available at https://www.tue.nl/en/our-university/departments/chemical-engineering-and-chemistry/the-department/research-evaluation/

5 The first Physics and Chemistry sector plan was initiated in 2009, followed by a second Chemistry sector plan running from 2018-2024: https://www.sectorplan-betatechniek.nl. The sector plan budget for Chemistry and Chemical Engineering is an additional governmental budget intended to focus on and enforce the fundamental basis of the technical sciences at the Dutch universities and can be applied to the expansion of research capacity and attracting and retaining of talent.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3. Strategy during the review period

Building on its shared mission, the long-term strategy of the department is and remains focused on excellence in education and scientific and technological research with important contributions to industry and society in a financially sound organization. Since the establishment of the department in 1957, the actual research program has largely been determined by the visionary achievements of its individual members in fulfilling this long-term strategy and shared mission. Examples include the creation of the Dutch Polymer Institute (DPI), a public-private partnership to perform pre-competitive research into polymers and their applications (originator and first scientific director: Prof. Piet Lemstra), the Dutch National Research School 'Combination Catalysis Controlled by Chemical Design' (NRSC-Catalysis; Prof. Rutger van Santen as scientific director) and the leading interdisciplinary TU/e Institute of Complex Molecular Systems (ICMS; Prof. Bert Meijer as founding director). A more recent example is the Advanced Research Center for Chemical Building Blocks Consortium (ARC CBBC), where TU/e is one of the founding fathers (Prof. Hans Kuipers as initiator).

A key element of the strategy is the focus on excellence in science and engineering and its connection to our societal role to educate talented engineers (master's level), professional designers (professional doctorate trainees) and scientists (PhD students). To propagate this, all scientific staff should have a significant scientific contribution. This is complemented with active participation in shaping the various educational programs of the department. To materialize our impact on industrial innovations and society, the department aims for strong connections and collaboration with relevant industries, research institutes and universities (both nationally and internationally). Moreover, the department provides active support for spin-off activities.

People

To fulfil our ambitions, people are our most important resource. Attracting (and retaining) talent is increasingly competitive. Unfettered fundamental research in industry has been largely replaced by market-oriented research goals. Because of these developments, new hires of scientific staff in the department now predominantly come from academia itself. Excellence in research and teaching remains the most important criterion in hiring. The new sector plan funds offer opportunities to reinforce strong existing activities and attract/retain top talent in new areas. Maximum use of available human and financial resources requires dedicated recruitment strategies. To scout and motivate scientists to apply for open positions, the department makes use of search committees composed of 4-5 scientific staff (from the department and from other departments in order to strengthen collaboration and for an independent view) with expertise in the selected scientific area of the vacancy that actively look for and approach (female) talent for a specific position. To retain people, expectations regarding performance and promotion are formulated. In terms of guidance and supervision, we focus on customization with dedicated approaches within the framework of TU/e policies that are aligned with individual needs in a strong network of professional support (e.g., HR advisors, including mentoring and professional mental support, financial advisors and the Department Board) which is accessible to everyone in the department. Together, direct supervisors and employees carry the primary responsibility for this, in line with the Collective Labor Agreement for Dutch universities.

Science

Earlier, Table 1 presented highlights of the areas of gravity that naturally evolve from our expertise in conjunction with the societal relevance of this. To fulfil our scientific ambitions, the department creates critical mass and focus centered around these areas of gravity. Aligned with this, the department strives for strong participation in prestigious research programs to acquire sufficient funding, to perform top-notch research at the forefront of science and technology and for investments in large infrastructure. As competition for external funding is high, both at a national and European level, scientific staff are forced to put substantial efforts into grant applications. This highly competitive funding environment requires careful evaluation to make well-informed decisions and explicit choices for a relatively small department covering a significant range of disciplines in chemical engineering and chemical sciences.

Societal relevance

To guarantee societal impact, the department actively participates in initiatives like the Dutch Science Agenda (NWA), public-private partnerships and the National Growth Fund. As the targeted societal challenges of energy, circularity and health require a multidisciplinary approach, this will be done in collaboration with scientists in the TU/e institutes of ICMS and EIRES, other TU/e departments and relevant industries, other institutes, and other universities. Open access publishing and participation in publications for the general public is encouraged.

Notes

4. Major developments during the review period

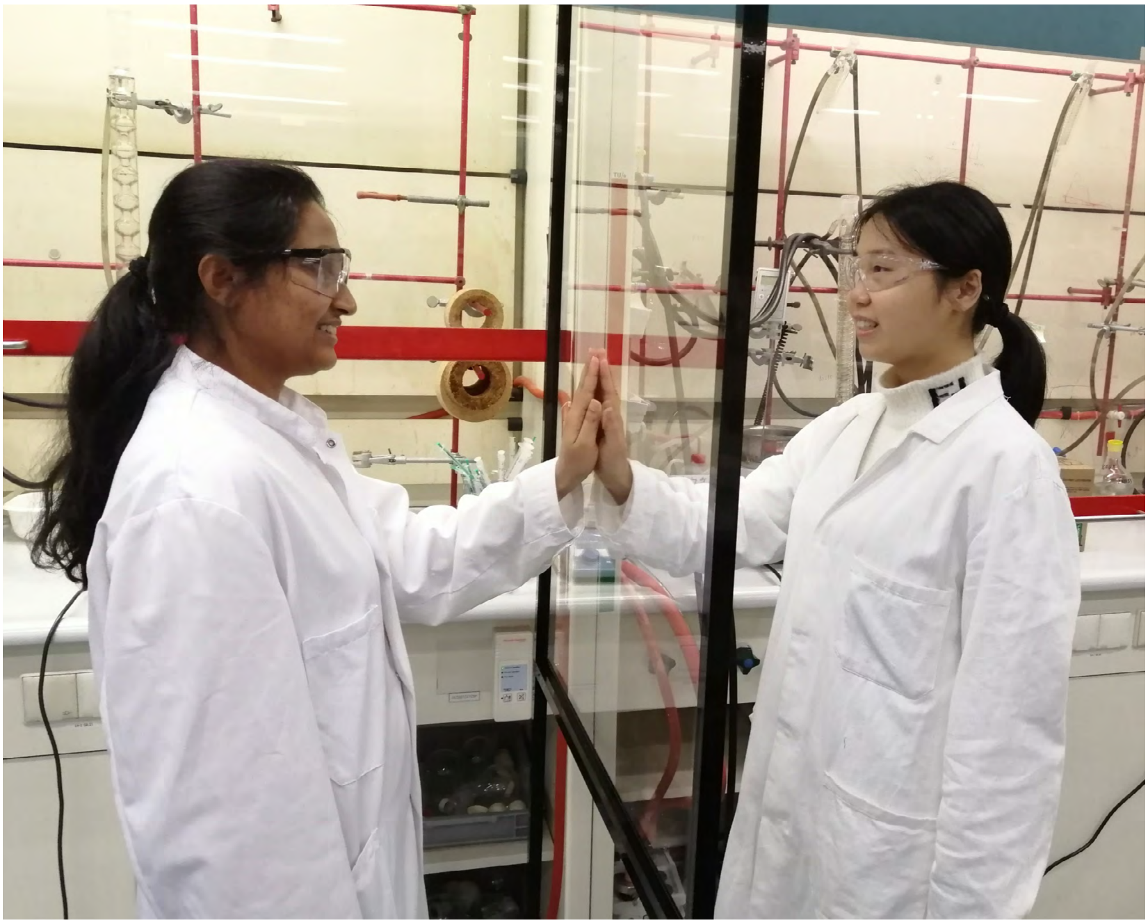
Before presenting factual evidence and narratives on scientific and societal accomplishments, several major external developments that impacted the department during the reporting period are described below.

- The reorganization of the department (formally finalized in 2015) created a focus on two research domains: Molecular Systems & Materials Chemistry (MSMC) and Chemical & Process Technology (CPT), directly connected to the two master tracks in the education program Chemical Engineering and Chemistry as part of the TU/e Graduate School (established in 2014). Direct university funding, national Gravitation programs and sector plan budget created opportunities to enforce the expertise areas defined in the department blueprint (2015-2021) and described in the sector plan report. In the previous sector plan fund for physics and chemistry, budget was used predominantly to increase critical mass in both the research domains of Molecular Systems & Materials Chemistry and Chemical & Process Technology. Complementary to funding received from the TU/e research institutes of ICMS and EIRES, the most recent sector plan fund for beta and technology was mostly used for hires in newly-defined expertise areas, resulting in significant critical mass bridging the two research domains and expanding and enhancing our expertise in molecules, materials and processes. Additionally, the department invested in the strongly emerging field of electrochemical conversions and energy storage processes. Details on specific appointments during the review period are presented under 'evidence' further in this report and in Table 1 in Appendix A.

- During the review period, the role of TU/e institutes has increased. The institutes bring together researchers from various departments in areas such as mathematics, physics, biology, chemistry and engineering to stimulate education and interdisciplinary research in emerging fields of science and technology. A large number of researchers of the department actively participate in the Institute for Complex Molecular Systems (ICMS). This is well-visible in the focus of the institute: mastering complexity through a deeper understanding of how matter – both natural and artificial – self-organizes into functional molecular systems. During the review period, a new institute, the Eindhoven Institute for Renewable Energy Systems (EIRES), was founded that also strongly builds on the research and expertise of the department (see e.g., case studies 3 and 4 in Appendix B). EIRES brings together TU/e researchers working on materials, systems and processes for energy storage and conversion with a focus on solving fundamental challenges underlying the development of systems with the potential for rapid upscaling and market penetration.

- During the review period, the landscape for research grants and contract research (external funding) significantly changed. In the past, resources for funding provided by the Dutch government were distributed competitively through the Dutch Research Council (NWO) as personal grants or for smaller consortia. This latter aspect has now changed to funding for large, highly-complex consortia of academia, universities of applied science, research institutes, industrial partners and societal organizations. Despite an overall increase in financial resources, the level of competition for such large prestigious grants has increased and is enormous. In addition, part of the governmental funding nowadays is also competitively distributed through other means than by NWO (e.g., the Growth Fund). Although the department is well-equipped scientifically, this complexity strongly increases the efforts required.

- The COVID-19 pandemic has had a severe impact on the department's research and education. At the start of the pandemic, the department building and experimental facilities were closed to all research for eight weeks. After this period, on-campus experimental research was possible to a certain extent but was limited to small groups of researchers to guarantee social distancing rules. The opening and closing times of the building were enhanced to allow work in shifts. All employees were encouraged to perform non-experimental work at home using the department's office supplies (including chairs, computer accessories, etc.). The impact on the research of many researchers was significant, delaying some projects and increasing theoretical and modeling components in many research projects. Upon request and with solid arguments, the university is providing additional financial resources and extensions of contracts for temporary researchers that have experienced delays due to COVID-19.



- During the recent period, the organization of research staff in academia has changed from a more hierarchical structure towards an organization in which independent researchers with interconnected expertise work together in larger research groups. Scientific staff members are expected to develop themselves into independent researchers early in their careers. New hires preferably initiate new research areas with optimum synergistic overlap with existing activities while maintaining the topical balance of competences in the department. At the same time, multidisciplinary research at the interface between disciplines is stimulated. However, full independence does not exist and all scientific staff share a joint responsibility for the education and research program of the department. Within this context of scientific independence and shared responsibility, the department gives room to all staff members to develop their own independent scientific profile, as well as to tailored scientific development and differentiation in career paths. In alignment with this, the quality of science and education in the department should remain at the same high level, which puts a strong responsibility on all scientists and on the definition of career paths and criteria for selection and promotion. Also, adapting the current organization to this rapidly changing academic landscape requires new organizational structures and an alignment of expectations. The department has the responsibility to find a balance involving all of these aspects.


HUMIDITY
HUMIDITY
CATHODE
ANODE BP
CATHODE BP

5. Evidence and accomplishments

5.1. INTRODUCTION

In line with its mission, the main ambitions of the department during the reporting period were to maintain its strong position in key societally-relevant areas and to strengthen the identified areas of gravity despite the pressure on financial resources. This requires investments in people and excellent research at the forefront of science and technology with a societal impact. Concrete actions and results related to these aspects achieved during the review period are described below and are divided into two sections: research quality and societal impact.

5.2. RESEARCH QUALITY

People

In the last six years – with the availability of resources due to additional sector plan funds, the promotion of scientific staff of the department to positions at other universities, and natural attrition – the department has been able to strengthen its staff in supramolecular and polymer chemistry, physical chemistry, separation technology, inorganic materials and catalysis, and chemical reactor engineering in line with the identified areas of gravity of the department (Table 1, presented earlier). Also, the department's chain of knowledge in the field of electrochemical energy conversion and storage has been empowered. A detailed list of all new hires in the review period is given in Table 1, Appendix A.

In the Molecular Systems and Materials Chemistry domain, Prof. Schenning and Prof. Sommerdijk were promoted to the rank of full professor, establishing new groups in 2015 in response to the retirements of Prof. Broer and Prof. de With (both in 2015). Prof. Schenning works on stimuli-responsive functional materials and devices. This activity was reinforced with the appointment of Dr. Liu (female), who uses concepts of synthetic organic chemistry to design macroscopic materials for morphology and shape control. Prof. Sommerdijk left to Radboud University Nijmegen (RUN) in 2019. Prof. Tuinier moved from DSM to TU/e in 2015 and heads the Physical Chemistry group. Dr. Vis joined that group as an assistant professor in October 2019, bringing theoretical and experimental expertise in the field of macromolecular mixtures.
Prof. van Hest was appointed as a full professor in Bio-Organic Chemistry in 2016. Dr. Abdelmohsen joined as an assistant professor in 2018, aiming for the design and fabrication of nanomotors. Prof. Voets (female) was appointed as a full professor (Self-Organizing Soft Matter) in 2018, with her initial appointment stemming from the first sector plan fund. In 2022 (outside of the scope of the review period), this activity was strengthened with Dr. Moerman appointed as assistant professor. In 2019, Prof. Palmans (female) was promoted to full professor, focusing on supramolecular chemistry and catalysis. In the same year, Dr. Vantomme (female) was appointed as an assistant professor in the field of supramolecular materials chemistry in this group. In 2020, Prof. Tomovic moved from BASF, joining the department with expertise in polymer performance materials and a strong focus on polymerization strategies for the creation of novel polymers with inherent recyclability for reuse. In 2022 (outside of the scope of the reviewing period), this activity was strengthened by Dr. Eisenreich appointed as assistant professor.

In the Chemical and Process Technology domain, Prof. Schouten, Prof. Gallucci, Prof. Van der Schaaf, Dr. Noël, Dr. de Groot and Dr. Neira d'Angelo (female) are active on the theme of sustainable process engineering, bringing together expertise in chemical reactor design, process intensification, renewables conversion and flow chemistry. In 2019, Prof. Rebrov (Energy-Intensified Chemical Reaction Engineering) joined in anticipation of the retirement of Prof. Schouten in 2020. In 2020, Dr. Noël was promoted to professor at the University of Amsterdam (UvA). The intensive collaboration between TU/e (catalysis) and the University of Twente (process technology) and between TU/e and Utrecht University (catalysis) forms the core of the MCEC Gravitation program, which focuses on establishing a multi-scale modeling base in catalytic conversion processes. This program has led to a new activity in mesoscale modeling (Dr. Filot, tenured since 2018), linking the quantum-chemical modeling of catalytic events to reactor modeling. Prof. Nijmeijer (female) succeeded Prof. Kroon in 2016 as the chair of Membrane Materials and Processes, the original position being funded by the first sector plan fund in 2009. This group focuses on the design and development of polymer membranes to separate molecular mixtures for sustainable processes. At the same time, associate professor Dr. Borneman (polymer membrane formation) joined; in 2019, this activity was further strengthened by Dr. Forner-Cuenca (electrochemical membrane processes) appointed as assistant professor. In the field of catalysis, the TU/e-UU Alliance program has led to the appointments of Dr. Hofmann on solar fuels catalysis (2014; since 2020, full professor at TU Darmstadt), Dr. Kosinov on inorganic materials and catalysis (2016) and Dr. Costa-Figueiredo (female) on inorganic electrochemistry (2019). Together, the new junior staff (Forner-Cuenca, de Groot, Costa-Figueiredo) develop a chain of knowledge in the areas of the electrochemical conversion to fuels and chemicals and energy storage processes. In 2016, the activities of Prof. Kuipers were strengthened by appointing Dr. Baltussen (female) and Dr. Buist appointed as assistant professor to enhance the research on the multi-scale modeling of multiphase flows.

The focused investments described above, together with the scientific excellence of several researchers, has resulted in a further strengthening of the internationally leading position of the department in the identified areas of gravity on molecules & materials for health and materials & processes for energy applications.

In line with the vision on internal career paths, the department appointed several promising staff to the rank of full professor, e.g., Voets (female; 2018), Gallucci (2018), Palmans (female; 2019) and Van der Schaaf (2020). Besides senior appointments, the department was able to attract several early-career researchers with diverse international backgrounds. In recent years, the department mostly invested in full professorships and young talent. Simultaneously, some people at the associate professor level left the department for promotions at other universities. This has resulted in a solid fundament of senior scientists complemented by a strong base of junior staff. In the coming years, the strengthening of mid-career staff requires attention. As of 2020, 35% of the scientific staff are international. A dedicated program of the department and the active search committees to improve the gender balance (despite efforts that were not successful in all recruitment trajectories) led to the appointment of several female researchers during the review period (Table 4), resulting in a gradual increase in the relative amount of female scientific staff from 15% in 2015 to 26% in 2021. Detailed numbers at the different career levels can be found in Table 2 in Appendix A.

Table 4: Number of female, male and total scientific staff in the department.

Year	2015	2017	2019	2021
Number of female staff	7 (15%)	6 (14%)	9 (21%)	10 (26%)
Number of male staff	39 (85%)	37 (86%)	34 (79%)	29 (74%)
Total number of staff	46	43	43	39

In summary, the department has been able to strengthen its foundation, rooted in the thematic domains of molecules, materials and processes in the application areas of energy, circularity and health, by reinforcing staff with early-career and experienced hires, promoting promising researchers to the rank of full professor and establishing a more diverse staff. As science and education are strongly intertwined, the investments described above allow our scientists to educate students and young researchers for their future responsibility of solving the emerging societal challenges in these domains. The importance of this is specifically highlighted in case studies 1 and 2 in Appendix B.

Science

Despite COVID-19 and the increasing level of competition over the years, the department is and remains successful in acquiring substantial highly competitive research grants from the Dutch Research Council (NWO; e.g. excellence programs (Gravitation programs) and up-and-coming talent programs (Talent Scheme)), European Union programs (FP7, Horizon 2020; including ERC and EIC programs) and contract research through public-private partnerships (Chemelot InSciTe, ARC CBBC, DPI, ISPT) or bilateral contract research with private partners (see societal impact). The table below summarizes the major research grants obtained in scientific competition during the review period. The large impact of such grants to perform research at the forefront of science and technology and its importance in educating and inspiring young people is highlighted in case study 2 in Appendix B. As evidenced in Tables 2 and 3 in Appendix B, scientists in the department are highly valued in a national and international context given the extensive number of marks of recognition received from peers and their memberships of prominent organizations and scientific committees.

Table 5: Selection of most prestigious scientific research grants acquired during the review period.

Grant description	Recipient (year)
Spinoza Prizes (NWO)	
Prof. René Janssen	Spinoza Prize (2015)
Prof. Jan van Hest	Spinoza Prize (2020)
Gravitation program (NWO)	
MCEC	Netherlands Center for Multiscale Catalytic Energy Conversion (2014-2024) Principal investigators: Hans Kuipers, Rutger van Santen, Emiel Hensen
FMS	Functional Molecular Systems (2013-2023) Principal investigators: Bert Meijer, René Janssen, Jan van Hest
IPM	Interactive Polymeric Materials Research Center (2022-2032) Principal investigators: Jan van Hest, Patricia Dankers (Department of Biomedical Engineering)
Talent Scheme (NWO)	
Vidi	Ilja Voets (2015), Timothy Noël (2015)
Veni	Danqing Liu (2016), Koen Hendriks (2017), Mark Vis (2017), Ivo Filot (2017), Ghislaine Vantomme (2017), Mengmeng Li (2018), Antoni Forner-Cuenca (2019), Anat Akiva (2019), Roderick Tas (2020), Fabian Eisenreich (2021)
ERC grants (European Union)	
ERC Advanced Grant	Dick Broer (2015), Jan van Hest (2016), Bert Meijer (2018), Nico Sommerdijk (2018)
ERC Consolidator Grant	Evgeny Pidko (2016), Ilja Voets (2021)
ERC Starting Grant	Antoni Forner-Cuenca (2021)
ERC Proof-of-Concept Grant	Ilja Voets (2017), Volker Hessel (2017), Ilja Voets (2019)

Table 6 gives an overview of the research outputs during the review period. The quality and impact of the outputs are the leading criteria for the department, and the staff members of the department are highly successful in this respect as is evident from the substantial number of refereed publications in the top journals of the respective disciplines and in multidisciplinary journals. Five key publications published by each group during the review period are given in the research group descriptions in the additional booklet attached to this report. The research outcomes are also presented at major national and international conferences. Staff members are sought after for lectures at conferences, universities, research institutes and private companies around the world.

Table 6: Research outputs in the period 2015-2021.

Yearly output	2015	2016	2017	2018	2019	2020	2021
Refereed articles	408	433	432	424	373	441	377
Book chapters	24	10	24	21	7	9	2
PhD theses	44	38	33	36	39	45	44
Professional publications	13	9	8	10	12	5	4
FWCI	1.8	1.8	1.88	1.6	1.9	1.5	1.5
Publications in top 1% journals	11.3%	13.4%	12.5%	9.5%	9.3%	10.7%	13.4%
Publications in top 10% journals	72.3%	73.9%	70.7%	68.2%	63.1%	58.9%	60.0%
Outputs in top 1% citations	2.5%	2.5%	2.0%	0.9%	3.6%	0.8%	0.6%
Outputs in top 10% citations	20.0%	22.7%	25.4%	21.8%	21.4%	16.6%	15.1%

The department has a long tradition of scientific excellence, as is evident from the large number of high-quality publications in mostly Q1 journals (top 25% journals in a particular research field). In fact, an average of more than ~40% of the publications are in top 10% journals. The main purpose of the department in publishing papers is to inform peers about discoveries, thereby advancing science and technology. Prestige is an obvious criterion to target such top-tier journals. Hence, most of the staff regularly make efforts to publish their most profound research outcomes in general journals because of the higher visibility and broader dissemination.

The publication landscape is in transition. The total number of manuscripts submitted worldwide has significantly increased and open access publishing is obligatory for projects funded by e.g., the Dutch Research Council and the European Commission. Most of the publications of the department (~80%) are open access nowadays (Table 7) in order to make research available to readers at no cost. TU/e and grant organizations encourage open access publishing. TU/e has created a website with information on open access publishing and provides dedicated support from library experts. At a national level, a website listing journal agreements and the associated costs for university researchers is available. The significant share of academic-corporate publications (ca. 15%) underpins the successful collaboration with industrial partners on frontier topics in science and technology.

Table 7: Percentage of open access publishing of the department in the period 2015-2021.

Year of publication	2013	2015	2017	2019	2021
Open access (%)[1]	18	42	68	70	80

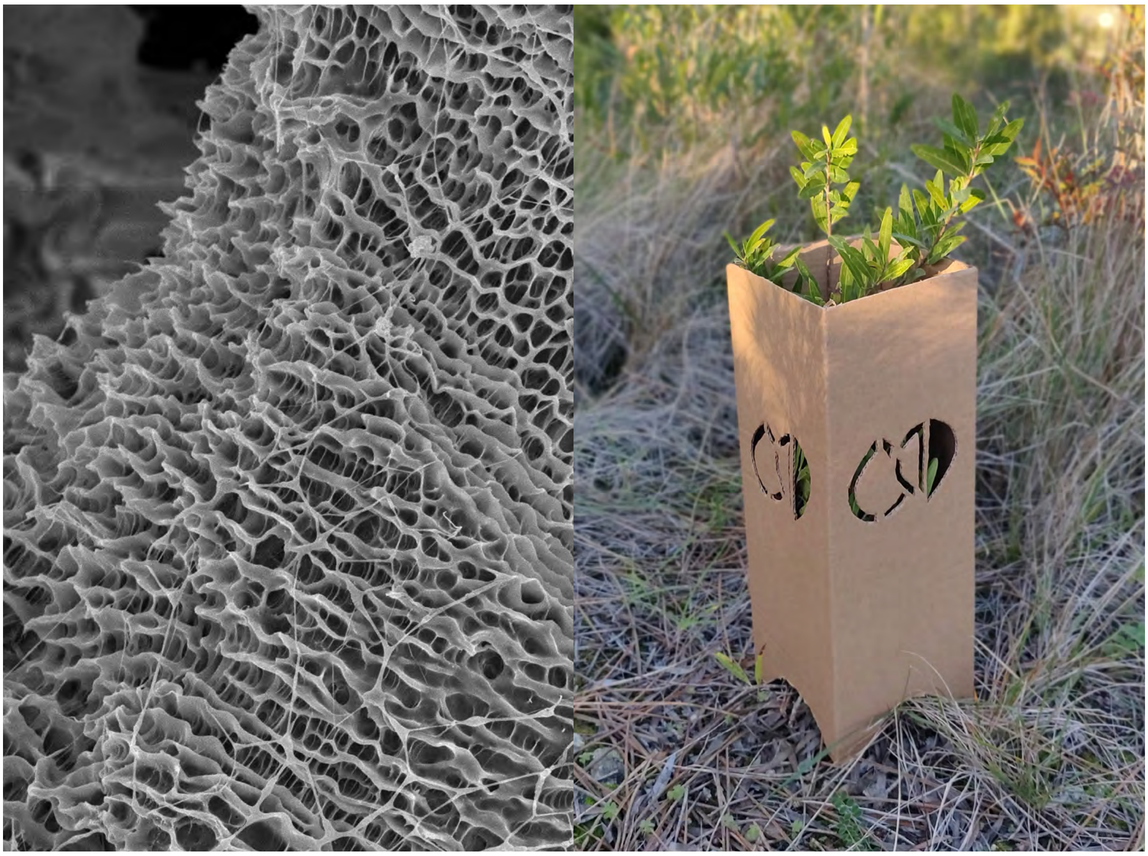
[1] Peer-reviewed publications in scientific journals (pre- and post-print versions included)

Most of the above is part of a self-sustaining culture in the department without written rules (except for rules regarding open access publishing from funding agencies). The consensus is that quality is more important than quantity. This is especially advocated with respect to publications in the framework of PhD projects, which make up the largest share of the scientific output.

5.3. RELEVANCE TO SOCIETY

As stated in the introduction, recent global developments strongly show the importance of science to society and scientists in the department have a strong sense of responsibility regarding their contribution to challenges related to energy, circularity and health, both in educating people and in performing research with a societal impact. The four case studies in Appendix B all provide clear evidence of this.

Other evidence includes the leading position of the department in several public-private partnership programs. The Chemelot Institute for Science and Technology (InSciTe) is a partnership set up in 2015 by TU/e, DSM, Maastricht University, Maastricht University Medical Center and the Province of Limburg. The aim of this institute is to develop and apply the production of biobased building blocks and biomedical materials with a focus on technical validation. More than €75 M has been invested in projects, leading to the employment of more than 100 people. The department has been mainly involved in the biobased domain. Highlights include the operation of a biobased pilot plant, the start-up company Vertoro (see case study 4 in Appendix B), several patents and license deals, and over 100 scientific publications.



During the review period, TU/e also founded the *Advanced Research Center Chemical Building Blocks Consortium (ARC CBBC)* with Utrecht University and the University of Groningen (UG) in 2019. This national research center developed an advanced research program aimed at chemical building blocks for novel sustainable energy and materials. ARC CBBC is a public-private organization in which academic (UU, TU/e and UG as founding fathers), industrial (AkzoNobel, BASF, Nouryon and Shell) and governmental partners cooperate on themes related to functional materials and specialties, coatings, and energy carriers. The academic members are elected and, of the 40 ARC CBBC members, eight originate from the department.

The department aims to achieve societal impact primarily through high-quality education and research in an intertwined manner. The quantity and quality of the graduates of the department therefore serves as an important parameter for societal relevance as well. In its most recent assessment, the Accreditation Organisation of the Netherlands and Flanders (NVAO) judged the bachelor's and master's programs of the department as "good" (the highest score) on all assessment criteria (intended learning outcomes, teaching learning environment, assessment and achieved learning outcomes). Because of the transition to English as the main language in all educational programs, the department was able to increase the number of students at both the bachelor's level (from 317 in 2015 to 353 in 2021) and master's level (from 180 in 2015 to 270 in 2021), which is the opposite of the demographic trends in the Netherlands, and could maintain a very significant inflow of students (see Table 5 in Appendix A).

Table 8 provides information regarding the duration and success rate of PhD trajectories in the department. The total annual inflow of PhD students remains constant, resulting in a continuously high number (>200) of PhD students. About 50% of students graduate in four years while the average time needed before graduation is 4.5 years. Scientific staff in the department are aware of the importance of timely graduation and actively steer this during e.g., PhD progress meetings and annual reviews. However, external factors do not always help with this. In the case of delays due to experimental limitations for which the PhD student cannot be held responsible, illness or serious personal reasons, the department is supportive in granting a well-substantiated extension of the contract.

Table 8: Information on the duration and success rate of the PhD program.

Enrollment			Success rate (graduated in ...)						
Starting year	*Enrolment (M/F)*	*Total*	*Year 4 or earlier*	*Year 4.5 or earlier*	*Year 5 or earlier*	*Year 6 or earlier*	*Year 7 or earlier*	*Not yet finished*	*Dis-continued*
2013	21 / 11	32	17 / 53%	23 / 72%	24 / 75%	29 / 91%	-	-	3 / 9%
2014	32 / 13	45	20 / 44%	29 / 64%	33 / 73%	40 / 89%	-	3 / 7%	2 / 4%
2015	36 / 7	43	21 / 49%	30 / 70%	37 / 86%	40 / 93%	-	2 / 5%	1 / 2%
2016	35 / 12	47	23 / 49%	36 / 77%	40 / 85%	41 / 87% [1]	-	2 / 4%	4 / 9%
2017	39 / 14	53	24 / 45%	35 / 66%	38 / 72% [1]	-	-	14 / 26% [1]	1 / 2%
Total	163 / 57	220	105 / 48%	153 / 70%	172 / 78%	188 / 85% [1]		21 / 10% [1]	11 / 5%

[1] Data taken into account until June 1, 2022.

Societal impact is also achieved through the creation of new and reliable knowledge and technology and its successful implementation in society. This is achieved, among other ways, through collaboration with industrial partners, scientific colleagues and other societal organizations in bilateral constructs or larger programs. Typical examples of such programs include the ARC CBBC, the Institute for Sustainable Process Technology (ISPT), the Dutch Polymer Institute (DPI), the Materials Innovation Institute (M2i), NanoNextNL, CatchBio and Chemelot InSciTe. The research groups work with a larger number of global partners in the chemical industry, including AkzoNobel, BASF, Dow, DSM, Johnson Matthey, ENGIE, Nouryon, Philips, SABIC, Sekisui and Shell. The department obtains, on average, 40% of all external funding via contract research with industry and has a relatively large number of co-publications with industry (~15 %). TU/e is consistently at the top of the ranking of global universities that co-publish with industry. Alongside part-time professors from industry (Table 6 in Appendix A) originating from strong collaborations between the scientific staff in the department and Dow, Shell and AkzoNobel/Nobian/Nouryon, the researchers are highly entrepreneurial, with several patents submitted every year (Table 7 in Appendix B) and a highly successful portfolio of spin-off and start-up companies that make use of the know-how gained in the department. During the review period, nine spin-off companies started during the review period. Some examples of spin-off/start-up companies that originated in the department, that started in the past as a result of research and that are still active include: SymoChem (2000), SupraPolix (2003), PTG/e (2004), Hybrid Catalysis (2005), FLOWID (2008), Peer+ (2008, acquired by Merck), SolarExcel (2011, acquired by DSM) and SpinID (2012, now part of FLOWID). During the review period, the following new companies were started: Emultech (emultech.nl), Ioniqa (ioniqa.com), Tusti (tusti.nl), FreshStrips, Sponsh (sponsh.co), Lusoco (lusoco.com), ClimAd (climadtechnology.com), Vertoro (vertoro.com) and H2Site (h2site.eu). The success of these spin-off efforts is evidenced by the fact that the Gouden Kiem for the best collaboration in chemistry between a start-up and a knowledge institution has been awarded to Tusti (2016), Fresh Strips (2017) and Sponsh (2018).

The staff members of the department are very active in outreach to the public as well. They give presentations and interviews on TV and the radio, provide their opinions on current affairs in newspapers, give guest lectures at schools and are frequently consulted by different societal actors. An example of the appreciation for these effects is the Academic Society Award of the Dutch Royal Institute of Engineers received by Prof. Kitty Nijmeijer. The department has an extensive outreach program for primary and secondary schools that includes, among other things, open days, the 'Experience Chemistry!' master class, facilities for profile paper research by secondary school students, a work week for secondary school students, pre-study opportunities and experience days. The target audience is mainly secondary school students with an interest in science and chemistry and teachers at primary and secondary schools. As an example, the department organized experience days in 2018 and 2022 for 85 teachers at secondary schools, updating them with the latest knowledge in the field of sustainability alongside lectures from the department, including a lecture by TU/e alumna Marjan van Loon, President Director of Shell.

5.4. TEACHING-RESEARCH NEXUS

An aspect of major importance, representing the societal impact of the department, is the quality and scope of its education. The scientists and engineers that we educate today carry the responsibility of solving major societal and technological challenges related to energy, circularity and health. The scientific staff in the department feel the strong responsibility to provide students and young researchers with a solid education addressing the fundamental questions related to these challenges and to equip them with a solid technological toolbox, including relevant soft skills allowing them to contribute to technological solutions. High-quality education and scientific and technological research are heavily intertwined in the department. All scientific staff members in the department contribute to teaching and also have their own distinct research lines. The scientific knowledge generated is integrated into the educational

program in the form of e.g., examples in lectures and exercises in courses. Other examples of the integration of education and research are the bachelor's and master's graduation projects that almost all students perform directly in one of the research groups. The educational program also offers project-based learning (design-based learning, DBL), which is typically carried out in the research groups of the department. Furthermore, students can actively participate in multidisciplinary TU/e-wide student teams to design, for instance, the house of the future or a solar car. Student teams like Solid, Core, iGEM, SensUs and VirTU/e are examples of teams to which our students contribute. Due to their multidisciplinary character, such projects are often performed in collaboration with students from other departments, TU/e institutes and industrial companies.

5.5. PHD POLICY AND TRAINING AND HUMAN RESOURCE POLICY

PhD policy and training

The department has more than 200 PhD students. The PhD students deliver the largest contribution to the research of the department. PhD trajectories are demanding and require support in terms of science and professional development tailored to the needs of the individual PhD student. Much of this is arranged at the individual level between a PhD candidate and the assigned supervisors in order to provide dedicated guidance, with support, monitoring and advising bodies (e.g., HR advisors, PhD Council) in place at the department level. In terms of mental health, TU/e has made support available to all PhD students in the form of a PhD counselor, a confidential counsellor, a company social worker and a company doctor. Each PhD student has at least two academic supervisors. All PhD students in the department can participate in content-based courses (regularly organized by graduate schools such as NIOK, OSPT, JMBC and the TU/e Graduate School) and courses related to soft skills (e.g., PROOF courses at a

TU/e level, including the obligatory course 'Scientific Integrity'). PhD students contribute to the educational tasks of the department (supervising guided self-study elements of bachelor's and master's courses, co-supervising laboratory courses and co-supervising bachelor's and master's graduation projects).

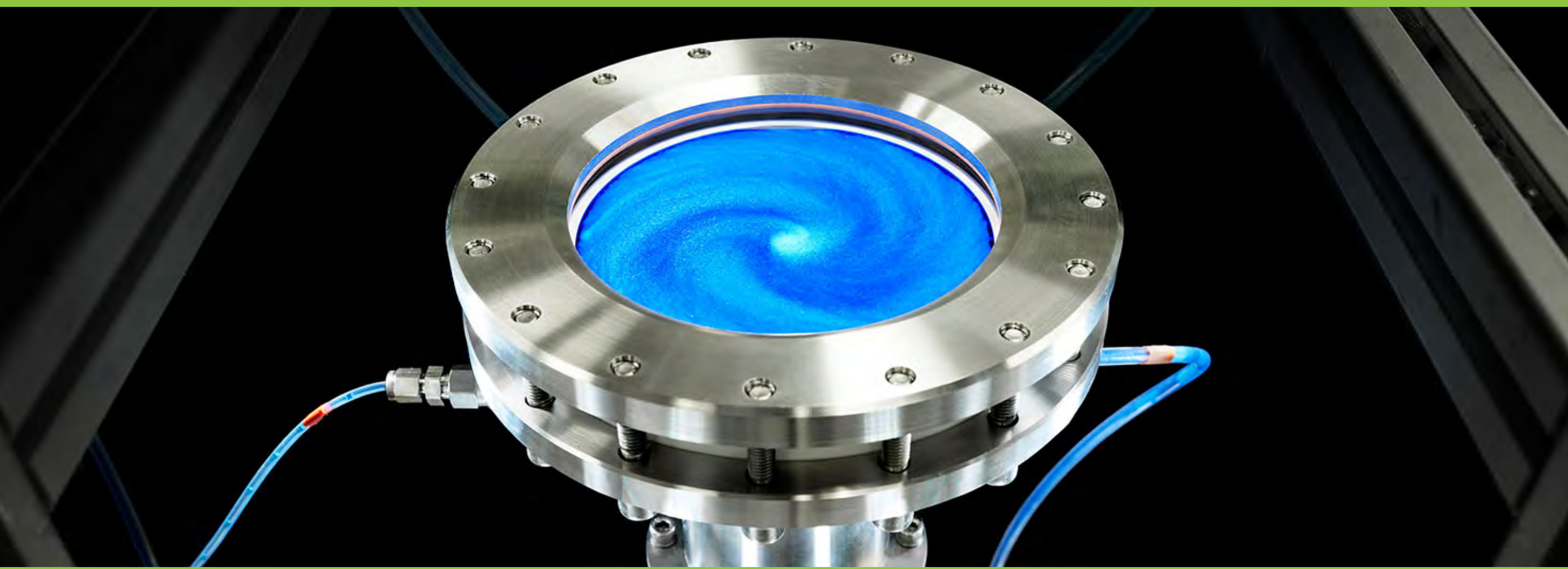
Agreements related to supervision, attendance of courses/conferences and overall research planning are set up by the PhD student and the supervisors upon mutual agreement and formally written down in the Training and Guidance Plan (TGP) three months after the start of the PhD trajectory and annually as part of annual interviews. During the years, additional courses and conferences not mentioned in the formal documents can and are regularly followed upon mutual agreement. Administrative aspects related to the onboarding and graduation of PhD students are registered in an administrative system for PhD trajectories (Hora Finita). All PhD candidates are formally enrolled in the TU/e Graduate School. Alongside annual interviews for all TU/e employees, PhD students have a formal evaluation after their first year (effectively around month 10). A self-reflection report by the PhD candidate, together with a written evaluation by the supervisors, form the basis for this meeting in order to evaluate whether the PhD student is expected to successfully complete his/her PhD.

At a higher level, the Department Board has regular meetings with the PhD Council of the department, composed of a PhD representative of each research group in the department. The PhD Council also organizes regular social gatherings for all PhD students in the department. In addition, the dean of the department has an exit meeting with each PhD student leaving the department. Close to 100% of PhD students find a new position quickly after graduation.

Human resource policy

The department wants to provide an inclusive environment with room for all students and employees. We embrace an open culture with freedom to discuss aspects related to science and personal aspects. To accommodate this, there are frequent meetings of the Department Board with e.g., the University Council, all professors, all scientific staff, the PhD Council, all management assistants and all research group representatives responsible for safety at the level of the research group. Recently, academic culture has also been addressed as an agenda item in all of these meetings. In terms of HR management, the department naturally complies with the agreements of the Collective Labor Agreement and TU/e policy.

In terms of academic promotions for staff, the department has well-defined criteria for promotion. In compliance with its mission, scientific quality remains a leading principle in all hiring/promotion trajectories. Candidates are evaluated according to formal appointment and promotion protocols. The departmental Promotions Committee, complete with additional experts related to the field of expertise of the candidate, advises the Department Board on the hiring/promotion of a candidate. The department keeps putting effort into increasing the amount of female scientific staff and is making use of specific search committees to proactively scout talented (female) candidates for open positions. For new hires at a scientific staff level, the department provides start-up packages (typically a PhD position and €50 k of investment for starting tenure-track staff; more extensive start-up packages are required when hiring senior staff, done in conjunction with the Executive Board). All senior scientific staff (i.e., associate and full professors) have *ius promovendi*.



6. Strategy for the next six years

6.1. SWOT ANALYSIS

During the last decade, the academic landscape and its interactions with the environment have largely changed. Since the previous research evaluation, the department has invested in its two scientific domains, as defined back in 2015: Molecular Systems & Materials Chemistry and Chemical & Process Technology. These investments have now resulted in critical mass over different length scales, from molecules to materials and processes (Table 1 in Chapter 1). Simultaneously, with the increasing importance of science to society, our research has naturally converged towards a focus on the grand societal challenges of energy, circularity and health. At TU/e level, the organization has changed from a central board and several departments focusing on specific scientific disciplines to an organization with departments and research institutes in which researchers from different disciplines (i.e., departments) join forces and collaborate on multidisciplinary topics directly connected to societal challenges, often in collaboration with other academic universities and universities of applied sciences, industrial partners and societal organizations. At a national level and globally, strategic alliances and partnerships are essential in contributing to solving complex societal challenges as this requires highly multidisciplinary approaches. At the same time, there is a strong battle for talent, impacting the attraction of top talent and support staff needed to stay at the forefront of science and technology. The SWOT analysis in Table 9 builds on these perspectives.

Table 9: SWOT analysis of the Department of Chemical Engineering and Chemistry.

	Strengths	Weaknesses
Internal	• Expertise over length scales covering knowledge chains (molecules, materials and processes) in focused application areas (energy, circularity and health) • Strong, state-of-the-art experimental infrastructure covering the department's expertise in chemistry and chemical engineering • Research and education are highly intertwined • Collaborative and entrepreneurial nature of the people across the department • Research staff in the department have strong ties and collaboration with other universities, industry and societal organizations in their respective fields of expertise	• Limited financial resources (limited direct university funding and very strong competition for external research funding) • Relatively small department with an unbalanced distribution of scientists in different career stages (relatively large number of young scientific staff but low number at associate professor level) • Retirement of internationally renowned scientific staff in the coming years • End of life of the Helix building, its laboratories that host the department and the basic infrastructure
	Opportunities	**Threats**
External	• Positioned in strong ecosystems with ample opportunities for collaboration • Solutions for societal challenges need multidisciplinary science and technology over length scales and strong collaboration • Strong increase in demand for well-educated, highly-skilled scientists and engineers (bachelor's, master's and PhD level) • Funding opportunities for large research programs (e.g., National Growth fund) • Large governmental investments granted to higher education ≥ 2023	• Complexity of the local, national and international playing fields • Battle for talent: unable to attract the top talent and support staff needed to stay at the forefront of science • Other academic institutions take a leading position in global collaboration across disciplines to solve societal challenges • Very strong competition for external research funding • Internal affairs can distract from empowerment at a national and global scale • Higher costs, longer delivery times of equipment and high inflation

6.2. STRATEGY FOR THE COMING YEARS

The societal challenges that we face nowadays are enormous: the energy transition from a fossil-based economy to sustainable energy sources combined with energy storage, the mitigation of climate change, the limited availability of resources (including clean water), and health and well-being for everyone. The Sustainable Development Goals defined by the United Nations call for strong, coordinated action on a global scale far beyond the boundaries of disciplines or organizations. As a department, we realize that we are a small player in this respect. However, with the preceding part of this report in mind, we are very well-positioned as a department to take responsibility and deliver our share in:

1. educating the scientists and engineers of the future.
2. advancing science and technology related to energy, circularity and health.

Positioning and societal relevance

The positioning of the department in a local, national and global context is artistically expressed in Figure 2 on the next page.

At the department level, we will further strengthen and enhance the three disciplinary expertise pillars of molecules, materials and processes and expand the chain of knowledge in these areas. We focus on the thematic application domains of energy, circularity and health. Within TU/e, the department will strengthen the collaboration and interaction with other departments (specifically the Departments of Biomedical Engineering, Applied Physics and Mechanical Engineering) to enlarge its chain of knowledge from molecules and materials to devices and

Figure 2: Vision of the department for the period 2022-2032.

processes in areas that lack resources at the department level. For example, strong collaboration with the Department of Biomedical Engineering expands the span of control towards devices and processes in the health domain, interaction with the Department of Applied Physics generates insights into the fundamentals of energy storage and transport and collaboration with the Department of Mechanical Engineering expands the impact in terms of process engineering and technology.

As the grand societal challenges have a strong multidisciplinary character requiring efforts across disciplines and cross-fertilization, scientists of the department will remain actively involved in the TU/e Eindhoven Institute for Renewable Energy Systems and the Institute for Complex Molecular Systems. With the increasing importance of big data and artificial intelligence, participation in the Eindhoven Artificial Intelligence Systems Institute may be considered.

Active participation in partnerships outside of TU/e remains one of the strategic targets of the department. The strong links with other Dutch universities and research institutes in the field of supramolecular chemistry, catalysis and process engineering via the current Gravitation programs will be continued with new initiatives. The strategic knowledge alliance with Utrecht University, Wageningen University and University Medical Center Utrecht will strengthen the impact of our research on circularity, biomass and food. Chemelot InSciTe enables the scaling up of our research on sustainable conversion processes. The strong involvement of the department in the public-private partnership Advanced Research Center Chemical Building Blocks Consortium (ARC CBBC) offers opportunities to strengthen the collaboration with dedicated partners from the chemical industry. Similar opportunities will arise from the new Mission-driven Top Sector and Innovation Policy of the Dutch government in which societal challenges such as climate change, the energy transition and circularity will be addressed. We initiate and actively seek out collaboration to define programs and shape proposals. This requires support at the department level for smaller disciplinary-oriented proposals and strong support at the TU/e level for large multidisciplinary proposals (e.g., the National Growth Fund).

To further strengthen our involvement and position outside of the ecosystem of TU/e, we will build on the collaborative and entrepreneurial nature of our people and make use of existing individual collaborations of our scientists to enhance coordinated collaboration in large research programs with other scientists, industries and societal organizations.

We will continue to stimulate and facilitate spin-off activities, such as through the Faculty of Impact program. TU/e has the intention to create an incubator on campus to support staff members and (PhD) students in creating a company based on research in the department. We will establish an academic and an industrial academic advisory board to mirror our ambitions and ideas in an environment of academic excellence and societal relevance.

Scientific excellence

The complexity of solutions for the grand societal challenges requires excellence in science and engineering, imagination, and creativity. We want to be and remain scientifically leading at a national and international level in the three points of gravity that naturally evolve from the department's shared expertise and focus areas: 1) interactive polymer materials, 2) molecules, materials and processes for energy conversion and storage and 3) molecules, materials and processes for the recovery of resources and circular processes.

At an international level, TU/e is clearly scientifically leading in interactive polymer materials. Over the last decades, a focused scientific strengthening of expertise and coordinated investments in polymer chemistry, polymer processing, functional supramolecular systems, advanced characterization and analysis methods of soft matter, chemical biology, and regenerative medicine have resulted in this very strong position in understanding complex molecular systems at the most fundamental level in order to shape the future of materials for health and life itself, amongst other things. Researchers from different disciplines and departments (Chemical Engineering, Biomedical Engineering, Applied Physics) collectively work together in this area in the Institute of Complex Molecular Systems. The recent granting of the Gravitation program Interactive Polymeric Materials Research Center (2022-2032) is, amongst others, a clear example of the continuing scientific excellence and strength in this area.

Following the example of interactive polymer materials, we want to strengthen and expand the department's activities in two areas over the coming decades: molecules, materials and processes for 1) energy conversion and storage and 2) the recovery of resources and circular processes. Although the exact focus requires further discussion, on the basis of recently attracted scientific talents and the department's involvement in the Eindhoven Institute of Renewable Energy Systems, coordinated actions in materials for energy conversion and storage will be set up to focus on catalyst and electrode materials, electrochemistry, membrane science, technology for photo and electrochemical conversions, and flow cell technology.
Regarding circularity, the focus will be on the selective recovery of components, circular polymers, sustainable conversion processes, process integration and intensified reactor concepts. To expand on this, strong coordinated activities and investments are required that build on an understanding of transport phenomena through interfaces, organic and inorganic materials chemistry, separation technology, chemical reactor engineering, multi-scale computational reactor engineering, big data, and artificial intelligence. Possibilities for a TU/e Institute for Circularity will be explored.

Engineer of the future

In times when there is an urgent need for scientists and engineers (bachelor's, master's and PhD levels), we have the responsibility as a university to educate these people. As a department, we are strongly committed to this responsibility. In the department, research and education are strongly intertwined and, in its educational program, the department combines a strong theoretical fundament with hands-on practical training. Teaching is done by researchers who are leaders in their field of expertise. The strong experimental component of our educational program naturally places constraints in terms of the number of students; however, we envision reasonable growth when resources are available. The recently allocated governmental investments can enhance this. To empower enthusiasm for science and technology, we actively reach out to younger generations and future students and organize educational activities to attract future students.

Infrastructure

Excellent research facilities and infrastructure are crucial for excellent research and to attract top talent. The department is hosted in the Helix building, which was constructed in 1998. To comply with safety and infrastructural requirements, renovation was planned for 2025 but this has been postponed to after 2030, stretching the limits in terms of its infrastructure. Sustainability is an integral part of our research. We will expand this to our operations and building and want to be climate-neutral by 2050.

The department currently hosts an impressive range of state-of-the-art equipment. For large equipment, the department heavily relies on strong competition for large research grants. Smaller project grants offer budget for dedicated smaller equipment. The availability and replacement of basic equipment is under pressure as this requires direct investments at the university level. To guarantee focused investments, a plan for infrastructure is being drafted at the department level and together with the research institutes. Recently, our microscopy facilities have been strongly upgraded. Despite increasing costs and delivery times combined with high inflation and strong competition for resources, strong investments in equipment beyond the boundaries of individual research groups are foreseen in the coming period, such as Roentgen diffraction (SAXS/WAXS), NMR, ICP, XPS and MRI.

Open science

As a department, we want to share the results of our research with other academics and scientists, industry and society. We intensively collaborate with industry in order to translate and transfer our results to industrial practice. We would also like to interact with industry in, for example, 'industry day' events organized on campus in which people from industry interact with scientists from the department through interactive lectures, workshops and site visits. Through our teaching, we educate the engineer of the future. To enhance enthusiasm for science and technology, we will reach out to society and, more specifically, to younger generations and future students. We put emphasis on outreach and the communication of our research to a general public. We organize educational days to attract students. To make our research available to others, we will target 100% open access publishing in the coming years. We follow the TU/e policy on data management and make research data available through the 4TU.ResearchData repository for science, engineering and design following FAIR principles.

HR policy

As a department, we have the ambition to be a center of inspired learning in chemical engineering and chemistry. This brings responsibilities when hiring new staff and in terms of the career development of staff in the department as we strive for excellence in research and education in the field of chemical engineering and chemistry. Everyone in the department shares the responsibility for this. Within a framework of excellence in science, globalization, increasing organizational complexity, and highly multidisciplinary societal challenges, our people are the most important aspect.

Vacancies due to people naturally leaving the department for promotion to other positions or retirement, combined with governmental resources ≥ 2023, give room to attract talent, especially at the more experienced level in order to balance the distribution of scientists at different career stages in the department. The current battle for talent places strong constraints, increasing the pressure on attracting and retaining the top talent and support staff needed to operate at the forefront of science. Within these boundaries, we will put extra efforts into hiring female talent, such as by making use of dedicated departmental search committees that were shown to be effective in the previous period and through the TU/e Irène Curie program giving preference to female candidates in the first six months of a recruitment process. Due to scarcity, recruitment processes require more time and effort from our scientific staff, and attractive and competitive start-up packages combined with state-of-the-art facilities and resources are even more essential to attracting and retaining talent.

Within the context of shared responsibility for science and education in the department, we do give room to everyone's talent, personal development and differentiation in career paths in order to retain talent following the Recognition & Rewards program of the Dutch Universities[6]. With this in mind, we foster and stimulate talent and talent development. We will invest in mentoring and dedicated talent programs offering, for example, leadership and advanced supervisory courses for talented, ambitious scientific staff. Special attention will be given to tailoring and diversifying

[6] Recognition and Rewards: Room for everyone's talent - towards a new balance in the recognition and rewards of academics; https://www.universiteitenvannederland.nl/recognitionandrewards/recognition-and-rewards/index.html

career paths depending on needs, academic advances and prospects. At the same time, we will invest in community building to avoid becoming a collection of individuals. We will build on the department's shared mission, defining shared goals by, for example, sharing successes and organizing departmental meetings and seminars or annual research and education days with all scientific and educational staff.

PhD policy and training

During the review period, the department relied on tailor-made, individual approaches, training and HR support for PhD students that best align with individual demands. Although this customized-for-individual-design approach is effective, we do realize that it requires much effort from supervisors. Besides, strong HR support and monitoring is needed to decrease the dependency of PhD students on supervisors and guarantee that every PhD has full access to HR support and possibilities for personal development. As the department has more than 200 PhD students, we will focus on the further standardization of general HR policies (supported by the HR system InSite) and monitoring such that dedicated, customized HR support can be provided when really necessary.
To facilitate the accessibility of HR, alongside providing information in person at the start of employment, HR employees will actively re-seek contact with PhD students half a year after employment to clarify information, listen to the experiences of the candidate and make HR more approachable. Moreover, HR is involved in the formal first-year evaluation of PhD students. Simultaneously, we will strengthen the monitoring of individual agreements (using e.g., Hora Finita) made between PhD students and supervisors, such as in annual interviews and regarding courses for personal development and progress. Also, the Department Board continues to have regular meetings with the PhD Council for the mutual exchange of information.
All PhD students can follow PROOF (PROviding Opportunities For PhD students) courses. PROOF courses are free of charge for all TU/e PhD students. Apart from offering tools to develop competencies on e.g., research skills, planning, supervision and scientific integrity (obligatory), the courses are also a platform to meet other TU/e PhD students. The department will actively promote and stimulate participation.

Academic culture

The department wants to provide an inclusive environment in which we work in a collegial, collaborative atmosphere with interaction, knowledge sharing and open debate and where all people can flourish and develop their talents while contributing to the shared mission of the department. We realize that this is not something to take for granted, especially not in an international academic environment with a wide diversity of people with different backgrounds. This requires investment and maintenance.

Scientific independence, scientific integrity and social safety are core values in our department. All employees and bachelor's/master's/PhD students in the department are trained to follow the TU/e Code of Conduct for Scientific Integrity based on trustworthiness, intellectual honesty, openness and independence. A complaints procedure for scientific integrity is in place for confidentially reporting scientific misconduct.[7] Moreover, at a TU/e level, there are confidential counsellors and an ombudsman that act independently and impartially and have no position of authority.

[7] assets.tue.nl/fileadmin/content/universiteit/Over_de_universiteit/integriteit/ Complaints_procedure_scientific_integrity_TUE_1-9-2014.pdf

To enhance discussion and increase awareness, we commit ourselves to coordinated actions to develop a shared academic culture where people feel welcome. Training courses on social safety and academic culture will be organized periodically. Moreover, social safety is added as a standard item to the agendas of all departmental meetings (e.g., the Council of Full Professors, scientific staff meetings, the PhD Council, management assistant meetings, lab safety meetings). As a recent example, all employees were strongly encouraged to watch Mindlab[8], a theater play offered at TU/e on scientific and social integrity.

We want to provide an open and inclusive environment where everyone feels welcome, valued and respected and where people learn, discuss and work for inspiration and the exchange of knowledge and scientific ideas. In this environment, we want to educate the engineer of the future and contribute to advances in science and technology in collaboration with other stakeholders to come to solutions for society related to energy, circularity and health.

[8] *Mindlab* is a theater play about a Dutch university and aims to facilitate a dialogue on social safety and academic culture; https://www.uu.nl/en/organisation/mindlab-a-theatre-performance-that-touches-at-the-heart-of-science-and-academia

7. Summary

The mission of the Department of Chemical Engineering and Chemistry of Eindhoven University of Technology (TU/e) is to be a center of inspired learning in chemical engineering and chemistry, encouraging the pursuit of new knowledge and innovative scholarship. We provide strong chemical engineering and chemistry education on solving complex societal problems and advancing basic science and technology. We do this in close collaboration and interaction with national and international partners from other universities, research institutes, industry and societal organizations in curiosity-driven research programs, strategic alliances, public-private partnerships and bilateral collaborations.

The research of the department focuses on two thematic domains: 1) Molecular Systems and Materials Chemistry, covering research involving atomic-scale molecular design and the nanoscale organization of new functional materials, and 2) Chemical and Process Technology, focusing on the design of integrated multiphase reactors, process engineering and equipment concepts. In line with this, the department hosts an impressive range of scientific, state-of-the-art equipment and facilities across the length scales of our expertise. The department has a collegial atmosphere with multiple collaborations and the sharing of expertise and scientific equipment.

The acquisition power of the department is very strong, with funding from research grants (fundamental research based on scientific excellence) and contract research (practical applications in collaboration with private partners) amounting to nearly twice the size of the direct university (fixed cost) funding. In line with our scientific focus, additional governmental funding (sector plan funds) is used to attract talent and strengthen our critical mass in supramolecular and polymer chemistry, physical chemistry and separation technology, catalysis and chemical reactor engineering, and electrochemical energy conversion and storage. The number of female scientific staff has increased from 15% in 2015 to 26% in 2021.

Our department is well-recognized, with a long list of prestigious grants and awards including two Spinoza Prize winners and two Gravitation programs (with an additional one very recently granted) from the Dutch Research Council (NWO) and multiple personal grants, including the Talent Scheme (NWO) and ERC grants. The department is a strategic partner in several large public-private partnerships, such as Chemelot InSciTe, ARC CBBC, DPI and ISPT, and has multiple smaller and bilateral collaborations with other knowledge institutes, industrial partners and societal organizations. The appreciation for the scientists in the department is confirmed by the extensive number of marks of recognition received from peers and the memberships of prominent organizations and scientific committees. Nowadays, 80% of our publications are open access. Quality and impact of research are leading criteria for the department, as evident from the substantial number of referred publications in the top journals of the respective disciplines and in multidisciplinary journals.

Our impact on society is most evident from the increasing number of people that we educate. Alongside ca. 350 bachelor's and ca. 250 master's students, our department hosts ca. 200 PhD students and a large number of visiting students and researchers. The large number of spin-off companies that started in the past and are still active, combined with the start of nine new spin-offs during the review period and the outreach activities of our scientific staff, also confirm the societal relevance of our research.

Building on its shared mission, the long-term strategy of the department is and remains focused on excellence in education and scientific and technological research with important contributions to industry and society in a financially sound organization. We will build on and expand the department's chain of knowledge on molecules, materials and processes in chemical engineering and chemistry. We want to provide an open and inclusive environment where everyone feels welcome, valued and respected and where people learn, discuss and work for inspiration and the exchange of knowledge and scientific ideas. In this environment, we will educate the engineer of the future and contribute to advances in science and technology in collaboration with other stakeholders regarding solutions for society related to energy, circularity and health.

Notes

Appendices

Appendix A: Additional tables

Table 1: New hires in the review period 2015-2021.

Name	Starting date	Male/ female	Position	Activity	Funding
R. (Remco) Tuinier	03/01/2015	M	Full professor	Physical Chemistry	CE&C
M.F. (Fernanda) Neira d'Angelo	04/15/2015	F	Assistant professor	Chemical Reactor Engineering	CE&C
D.C. (Kitty) Nijmeijer	02/01/2016	F	Full professor	Membrane Materials and Processes	CE&C
Z. (Zandrie) Borneman	04/01/2016	M	Associate professor	Membrane Materials and Processes	CE&C
K.A. (Kay) Buist	08/01/2016	M	Assistant professor	Multi-Scale Modeling of Multi-Phase Flows	CE&C
J.C.M. (Jan) van Hest	09/01/2016	M	Full professor	Bio-Organic Chemistry	ERC Advanced Grant
M.T. (Thijs) de Groot	10/01/2016	M	Assistant professor	Chemical Reactor Engineering	CE&C
M.W. (Maike) Baltussen	11/01/2016	F	Assistant professor	Multi-Scale Modeling of Multi-Phase Flows	CE&C
L.K.E.A. (Loai) Abdelmohsen	06/01/2017	M	Assistant professor	Bio-Organic Chemistry	CE&C
N. (Nikolay) Kosinov	04/09/2018	M	Assistant professor	Inorganic Materials and Catalysis	CE&C
D. (Danqing) Liu	02/01/2019	F	Assistant professor	Functional Organic Materials and Devices	Beta sector plan
A. (Antoni) Forner Cuenca	02/01/2019	M	Assistant professor	Membrane Materials and Processes	Beta sector plan
M.C. (Marta) Costa Figueiredo	04/01/2019	F	Assistant professor	Inorganic Materials and Catalysis	CE&C
G. (Ghislaine) Vantomme	04/16/2019	F	Assistant professor	Macro-Organic Chemistry	Beta sector plan
E. (Evgeny) Rebrov	08/19/2019	M	Full professor	Energy-Intensified Chemical Reaction Engineering	CE&C
M. (Mark) Vis	10/01/2019	M	Assistant professor	Physical Chemistry	Veni grant
Z. (Zeljko) Tomovic	06/01/2020	M	Full professor	Polymer Performance Materials	Beta sector plan

Table 2: Number of female, male and total scientific staff in the department per academic level.

Year	2015	2017	2019	2021
Assistant professors				
Number of female staff	3 (6.5%)	2 (5%)	5 (12%)	6 (15%)
Number of male staff	15 (33%)	14 (33%)	13 (30%)	12 (31%)
Total number of staff	**18**	**16**	**18**	**18**
Associate professors				
Number of female staff	3 (6.5%)	3 (7%)	1 (2%)	1 (2%)
Number of male staff	7 (15%)	6 (14%)	5 (12%)	3 (8%)
Total number of staff	**10**	**9**	**6**	**4**
Professors				
Number of female staff	1 (2%)	1 (2%)	3 (7%)	3 (8%)
Number of male staff	17 (37%)	17 (39%)	16 (37%)	14 (36%)
Total number of staff	**18**	**18**	**19**	**18**
Totals				
Total female staff	7	6	9	10
Total male staff	39	37	34	29
Total staff	**46**	**43**	**43**	**39**

Table 3: Selection of scientific grants, awards and scholarly prizes for the period 2015–2021.

Scientific grants, awards, scholarly prizes (2015 – 2021)	
Prize description	***Recipient (year)***
Spinoza Prize (NWO)	René Janssen (2015), Jan van Hest (2020)
RSC Soft Matter & Biophysical Chemistry Award	Nico Sommerdijk (2015)
Elected AAAS Fellow on Chemistry Section	Bert Meijer (2016)
Nagoya Gold Medal of Organic Chemistry	Bert Meijer (2017)
Dechema Award	Timothy Noël (2017)
ETH Zurich Medal	Antoni Forner-Cuenca (2017)
Chirality Medal	Bert Meijer (2018)
Academic Society Award of the Dutch Royal Institute of Engineers (KIVI)	Kitty Nijmeijer (2018)
KNCV Onderwijsprijs	Wendy Sanders (2018)
Doctorem Honoris Causa of the Freie Universität Berlin	Bert Meijer (2019)
ACS Biomacromolecules/Macromolecules Young Investigator Prize	Ilja Voets (2019)
KNCV Gold Medal	Ilja Voets (2019)
Honorary professorship of the Zhang Dayu Institute of Chemical Physics (DICP)	Hans Kuipers (2019)
ACS Applied Polymer Science Award	Dick Broer (2021)
Young Scientist Hydrogen Europe Award	Antoni Forner-Cuenca (2021)
Grant description	***Recipient (year)***
ERC Advanced Grant	Dick Broer (2015), Jan van Hest (2016), Bert Meijer (2018), Nico Sommerdijk (2018)
ERC Consolidator Grant	Evgeny Pidko (2016), Ilja Voets (2021)
ERC Starting Grant	Antoni Forner-Cuenca (2021)
ERC Proof-of-Concept Grant	Volker Hessel (2017), Ilja Voets (2017, 2019)
Talent Scheme (NWO/STW)	
• Vidi	Ilja Voets (2015), Timothy Noël (2015)
• Veni	Danqing Liu (2016), Koen Hendriks (2017), Mark Vis (2017), Ivo Filot (2017), Ghislaine Vantomme (2017), Mengmeng Li (2018), Antoni Forner-Cuenca (2019), Anat Akiva (2019), Roderick Tas (2020), Fabian Eisenreich (2021)
Gravitation program • Functional Molecular Systems	Bert Meijer, René Janssen, Jan van Hest (2013-2023)
• Netherlands Center for Multiscale Catalytic Energy Conversion	Hans Kuipers, Rutger van Santen, Emiel Hensen (2014-2024)
TOP-, TOP-PUNT, START-UP, LIFT, NWO-XS, NEMI, Demonstrator grants (NWO)	Martin van Sint Annaland (2017), Nico Sommerdijk & Albert Schenning (2018), Kitty Nijmeijer (2018, 2019 (2x)), Hans Kuipers (2018), Danqing Liu (2019), Antoni Forner-Cuenca (2020), Nikolay Kosinov (2020, 2021)

Table 4: Selection of memberships of prominent organizations and scientific committees for the period 2015-2021.

Memberships of prominent organizations and scientific committees (2015-2021)	
Member of	***Person (from...until...)***
Royal Netherlands Academy of Arts and Sciences (KNAW)	Hans Kuipers (since 2015) René Janssen (since 2011) Dick Broer (since 2010) Bert Meijer (since 2003) Rutger van Santen (since 2001) Jan van Hest (since 2019)
De Jonge Akademie (The Young Academy) of KNAW	Maaike Kroon (2012-2017, board member 2015-2016)
Royal Holland Society of Sciences and Humanities (KHMW)	Bert Meijer (since 1997) Jaap Schouten (since 2007) Jan van Hest (since 2021)
Honorary Fellow Chemical Research Society of India	Bert Meijer (since 2012)
Deutsche Akademie der Technikwissenschaften (acatech)	Bert Meijer (since 2012)
Academia Europaea	Bert Meijer (since 2012)
Nordrhein-Westfälische Akademie der Wissenshaften und der Künste	Bert Meijer (since 2014)
European Research Institute on Catalysis (ERIC) & Member of the European Cluster on Catalysis (ECC)	Emiel Hensen (2017)
Foreign member of the National Academy of Engineering (USA)	Rutger van Santen (since 2009)
Netherlands Academy of Technology and Innovation (AcTI)	Rutger van Santen
Fellow of the Royal Society of Chemistry	Emiel Hensen (2017)
Membership of scientific committees	
Member of	***Person (from...until...)***
Institute for Sustainable Process Technology (ISPT) • Vice-Chair of the Supervisory Board • Supervisory Board	 Jaap Schouten (2014-2016) Emiel Hensen (2016-present)
Netherlands Institute for Catalysis Research (NIOK) • Chairman of the Board	 Emiel Hensen (2012-present)
Dutch Research Council (NWO) • Member of the Governing Board • Member of the Board Division Chemical Sciences (CW) • Member of the Board of Directors (chair of NWO Applied and Engineering Sciences)	 Bert Meijer (2013-2015) Jaap Schouten (2016-2020) Jaap Schouten (2017-2019)

Table 5: Bachelor's and master's with a principal enrolment at CE&C during the evaluation period

Academic Year	Bachelor of Chemical Science & Engineering	Master of Chemical Engineering	Total for Chemical Engineering
2015/2016	317	180	497
2016/2017	321	218	539
2017/2018	335	238	573
2018/2019	376	242	619
2019/2020	385	264	649
2020/2021	387	289	676
2021/2022	353	270	623

Table 6: Part-time professors in the two thematic clusters of the department.

Research group	Part-time professors	Specialization	Affiliation	Appointed
Physical Chemistry	R.A.T.M. (Rolf) van Benthem C.F.J. (Jaap) den Doelder	Coating Technology Circular Polymers	DSM, Shell Dow	2002-2022 2016-2026
Inorganic Materials and Catalysis	Th. (Thomas) Weber	Solid-State Inorganic Chemistry	Shell	2011-2025
Chemical Reactor Engineering	J.T.F. (Jos) Keurentjes M.T. (Thijs) de Groot	Process Design Electrochemical Engineering	AkzoNobel, TNO Nobian, Nouryon	2007-2020 2016-2022
Micro Flow Chemistry and Process Technology	G.A. (Gunther) Kolb	Micro Flow Energy Technology	ICT-IMM	2013-2021
Inorganic Membranes and Membrane Reactors	E. (Emma) Palo	Process Design	KT-Kinetics Technologies	2018-2025

Table 7: Use of research products by societal groups.

Annual output	2015	2016	2017	2018	2019	2020	2021
Patent publication	6	6	7	8	11	2	3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Appendix B: Case studies

B.1. ARTIFICIAL CELLS

Context

One of the main challenges in medicine is to ensure that drugs reach the right target in the body and can perform their action without causing any side effects. This challenge has led to the development of the field of nanomedicine in which nanoparticles are used as delivery systems. However, until now, most nanomedicines still have not had the desired level of precision and also lack the ability to deliver drugs in a controlled and responsive manner based on interactions with the diseased tissue. To achieve this higher level of precision, we not only need to develop particles with greater affinity for certain cell types but also need to create particles that are adaptive to their environment and operate in a life-like manner. This challenge can be approached by combining nanomedicine with artificial cell research; the latter field of science is focused on building particles via a bottom-up approach with features that are reminiscent of living cells. This not only leads to a better understanding of how living cells operate but also allows us to construct particles that are able to interact effectively with living cells.

Our research

Introduction

Jan van Hest, head of the Bio-Organic Chemistry group, is a pioneer in the area of artificial cells and organelles, the organs of the cell. Van Hest and his team design and produce new materials and catalytic processes that combine artificially-produced molecules with biological components. These materials are used in biocatalysis and for biomedical applications such as drug delivery. They are also working on nanoreactors that can be deployed as artificial organelles in living cells to initiate reactions with enzymes. Van Hest is pioneering a new research field at the interface of polymer chemistry and biology. He was the first to produce polymersomes: empty spheres that can be filled, for example, with proteins or drugs and then inserted into a cell. With this technique, he succeeded in producing an artificial cell that simulates the complex behavior of a living cell. Van Hest also made polymer constructions that are similar to the cytoplasm in cells and managed to repair errors in biological cell processes using semipermeable spheres filled with proteins.

Current research

Spinoza laureate Jan van Hest and his group dream of producing completely artificial life: a system that can copy itself and adapt to changing conditions. The living cell can be regarded as the ultimate example of how molecular assembly leads to emergent behavior. One approach to unraveling how cellular complexity has evolved is to create artificial cells via a bottom-up molecular assembly approach. Artificial cells enable the investigation of biomolecular processes under highly controlled conditions. The information and insights that are subsequently obtained can then be translated to the field of active matter by endowing synthetic materials with life-like features.

In recent years, we have developed an artificial cell platform with a number of features that are reminiscent of living cells (Figure 1). The internal phase is composed of a coacervate which has a crowdedness similar to the cytosolic environment. The membrane is semipermeable, which allows for the exchange of molecules with the external milieu, and multiple compartments (artificial organelles) can be included in the coacervate core for the performance of cascade reactions with control over positional assembly.[1,2]

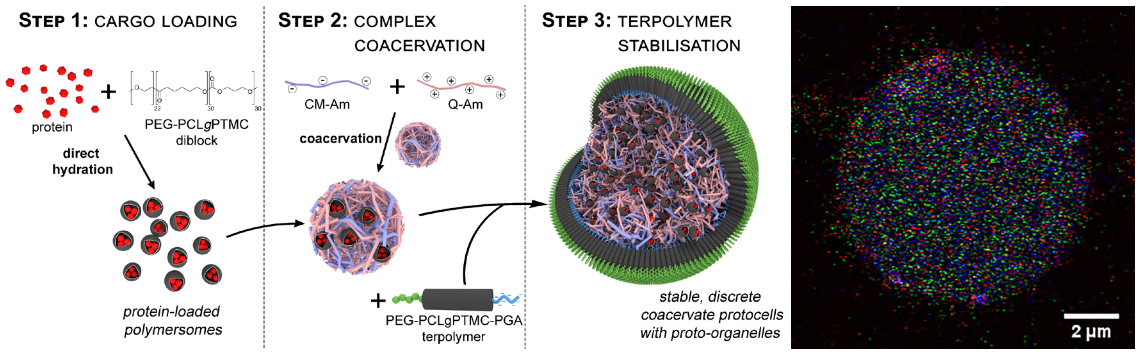

Figure 1: The process of forming a multicompartment artificial cell. The right picture shows a confocal image of an artificial cell loaded with three different polymersome nanoreactors, labeled with green, red and blue dyes.[2]

Furthermore, we have developed methods that allow them to take up and release proteins in a highly controlled manner.[3,4] This is of great interest as proteins are key biomolecules for intercellular communication between living cells. Within the framework of the Spinoza premium, we are exploring this artificial cell platform to achieve a higher level of sophistication in life-like behavior and create hybrid cell communities and tissues composed of artificial and living cells.

Artificial cells with life-like features

First of all, a highly characteristic feature of cellular behavior is intracellular communication and process control. This is achieved through the signal-induced positional assembly of different proteins which, when brought together, can activate down-stream cascade processes. To incorporate this feature into artificial cells, we have introduced the crucial scaffold protein 14-3-3 to our coacervates. This scaffold protein interacts with protein-binding partners when they are phosphorylated. These interactions can therefore be placed under the control of kinases and phosphatases, enzymes that regulate signaling cascades via (de)phosphorylation. Via this method, we can not only control the organization of protein networks within an artificial cell but also the direct uptake and release of proteins, thereby facilitating intercellular communication.

Biological processes are, in many cases, governed by stochasticity. As artificial cells are composed of a limited set of building blocks, local fluctuations could also be steered into emergent behavior. We have demonstrated that stochasticity can be employed to induce motility in artificial cells.[5] However, stochasticity, dynamics and protein release capacity can be further explored for use in artificial antigen-presenting cells for the activation of T cells in immunotherapy. The dynamic nature of the membrane allows the formation of protein micro-clusters that form the immunological synapse. Cytokine release from the artificial cells can be used to achieve a specific T cell response.

Towards artificial tissues

Artificial cells have been shown to be able to exchange small molecules between one another to activate a range of biological processes. It has also been possible to achieve one-way communication between a sender protocell and a receiving living cell. Although these are conceptually important steps forward, functional two-way communication is still elusive. With the support of the Spinoza premium, we are now applying the abovementioned dynamic protein localization methods to artificial cells to achieve spatiotemporally-controlled two-way communication with living cells and other artificial cells. We are currently investigating methods on how to functionally integrate artificial cells into living cell cultures. We have demonstrated that artificial cells loaded with growth factors can be stably introduced to 3D kidney organoids (Fig 2), where they are positioned to give spatiotemporal control over blood vessel growth. Furthermore, we have started to explore 3D bioprinting to organize artificial cells into tissue-like structures to provide an improved fundamental understanding of how cellular communication can be used to direct cell population behavior.

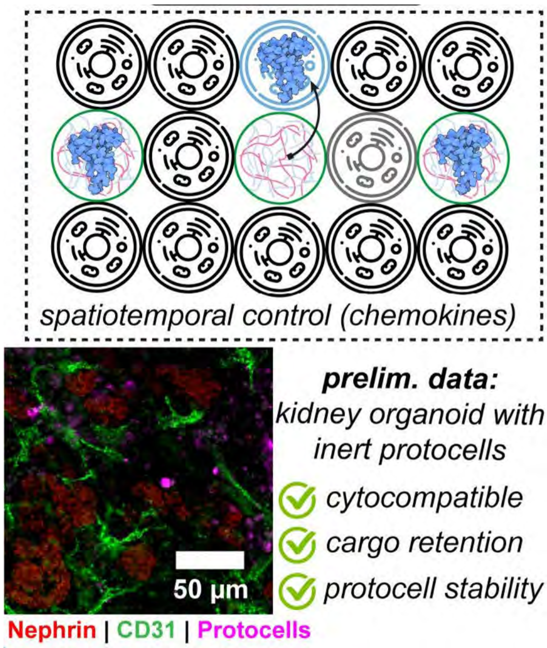

Figure 2: Top: schematic depicting the organization of living and artificial cells in which the latter provide growth factors locally to the living cell community. Bottom: organoid tissue sample in which both viable kidney cells and artificial cells are visible.

Societal impact

This line of research is ideal for the education of a next generation of scientists at the interface of chemistry and biology. Young researchers learn how to explore unchartered territories, which stimulates creative thinking and finding of one's own way. This creativity in molecular design also leads to materials with advanced functions. Within the Bio-Organic Chemistry group, we educate innovative researchers who can think across the borders of their own discipline and combine seemingly unrelated fields of knowledge. This is an asset not only for academic research but also for researchers who want to be active in commercial R&D.

The interdisciplinary approach of the Bio-Organic Chemistry group links the areas of chemistry and biomedical engineering seamlessly. It creates a continuum of scientific knowledge that we can offer to students on both sides.
Although the research can initially be characterized as curiosity-driven, many students also find their inspiration in the potential applications of the different materials and compartments in the field of biomedicine, which are never far away. In fact, van Hest actively seeks opportunities to translate his research into applications. Together with the company GATT, for example, he developed a surgical plaster that facilitates blood clotting. In addition, he owns a large number of patents and is the co-founder of the start-ups Encapson, Future Chemistry, Noviotech and Noviosense.

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B.2. LIGHT-RESPONSIVE LIQUID-CRYSTAL POLYMERS FOR SOFT ROBOTICS

Context

Soft robots are currently receiving a lot of attention as the use of compliant materials can improve their safety when working in close contact with fragile objects and humans. In contrast to hard robots, in which stiff segments limit the adaptability and versatility of devices, soft robots are fully comprised of soft materials that better emulate living, soft-bodied organisms and are more suitable for interactions with humans. However, promising applications are limited by the dependence on electrical or pneumatic tethers. To free soft robots from tethering to external or heavy on-board control units, the development and assembly of polymers which undergo macroscopic deformations in response to light is of great importance. Marina Pilz da Cunha's PhD research in the Stimuli-responsive Functional Materials & Devices group focused on light-responsive liquid crystal polymers. Her thesis reports on three highly innovative advancements related to untethered soft robotics: a fundamental understanding of light-responsive polymers, novel polymer materials and actuator assemblies for making robotic devices.

Our research

By combining two different stimuli-responsive materials in a single soft robotic device, she demonstrated how assemblies of soft actuators can expand device functionality and allow for the completion of multiple tasks that are not possible for single-component systems. In this part of Marina's research, collaboration with the Microsystems group of Jaap de Toonder in the Department of Mechanical Engineering was of crucial importance. Collaborating with researchers in the Department of Mechanical Engineering stimulated her immensely in thinking beyond a fundamental understanding and fabricating novel polymer materials, leading to light-driven robotic devices that can perform tasks.

For example, she advanced the state of the art in light-driven untethered soft robots by reporting a multi-functional robot based on liquid-crystalline polymers employing two different azobenzene derivatives making up the device's 'arms' or 'legs'. The first fully light-fueled mini-transporter can perform multi-directional locomotion and functions including pick-up, transportation and directional release of a cargo (Figure 1). She further developed an untethered multimodal light-driven aquatic device that integrates two different stimuli-responsive materials, a flexible magnetic polymer stem and a light-responsive azobenzene-doped liquid-crystal network gripper. The independent device segments can be orthogonally controlled to realize different functions: magnetic-driven stirring and light-triggered gripping within the same device.

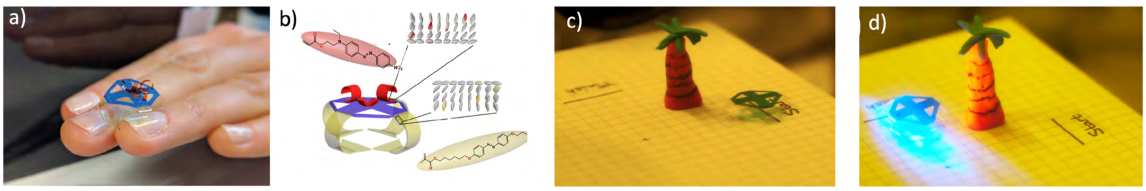


Figure 1: a) Transport mini-robot with light-responsive legs and arms, able to deliver cargo. b) The different appendages have different light-responsive molecules. c, d) The light-driven transporter in action, wirelessly walking and making a turn.

Societal impact

Marina has published 14 peer-reviewed papers on soft robotics in top-tier journals in the field (Proceedings of the National Academy of Sciences, Angewandte Chemie, Chemical Society Reviews, Matter, Advanced Sciences, Advanced Functional Materials, Advanced Optical Materials) which are highly cited. She completed her thesis, which contains seven experimental chapters, within 3.5 years and obtained her PhD cum laude. Her work has received extensive media attention, including interviews on Dutch radio, in the NRC Handelsblad newspaper and in National Geographic. Her mini-robot will be exhibited in Museum Boerhaave in Leiden.

B.3. ENGINEERING REACTORS AND DEVICES FOR HYDROGEN PRODUCTION

Context

Nowadays, European energy and transport systems are mainly based on fossil energy carriers, leading to major concerns regarding energy supply security, climate change, air pollution and the increasing prices of energy services. In the EU Sustainable Development Scenario, wind and solar will supply more than half of the total electricity in advanced economies by 2050, with renewables reaching 80% of the total generation in the EU.
An increasing share of renewables in the energy mix will strongly influence the flexibility requirements of the grid and will require adequate energy storage solutions to cope with the availability of renewable sources. Amongst energy storage solutions, hydrogen produced from electrolysis offers great promise as a flexible energy carrier that offers a perspective for both short and long-term energy storage. H_2 has the potential to ensure inter-seasonal energy storage, solving energy supply issues related to dark doldrums, for instance. Additionally, hydrogen can be transported with minimum losses, especially when stored in liquid energy carriers like ammonia.
A major challenge with hydrogen produced by water electrolysis is that it is still relatively expensive. This high price is not only driven by the price of electricity but also by the capital costs of electrolyzer plants. The latter is especially relevant when the electrolyzer is operated on the basis of an excess renewable electricity supply, implying that it will not be operational all year round.

The leading electrolysis techniques are alkaline and proton exchange membrane (PEM) electrolysis. PEM is a relatively new technology with high flexibility and compactness. Yet it depends on several critical raw materials (especially iridium), which is expected to be a major hurdle in its scale-up. In contrast, alkaline electrolysis is a technology that is already over a hundred years old. It is cheap but bulky and less flexible than PEM. Newer technologies such as anion exchange membranes (AEM) hold the promise of combining the advantages of alkaline and PEM but still need significant development.

Our research

The Sustainable Process Engineering group is developing improved alkaline and AEM electrolyzers that can achieve the same performance as PEM electrolyzers without the use of critical raw materials.
This can be achieved by making improvements to the design of alkaline electrolysis, including the use of thinner separators and more active electrocatalysts, the optimization of the operating parameters (temperature and pressure) and better cell designs. A challenge is that the design of electrolyzers has traditionally been carried out in a highly empirical way with a very limited fundamental understanding of key aspects such as mass transport and the influence of bubbles on the performance of electrolysis. It is therefore difficult to predict to what extent improvements will enhance electrolyzer performance.

One key 'mystery' is that the ohmic resistance in alkaline electrolyzers is much higher than what one would expect based on the properties of the separator. The implications of this high ohmic resistance are significant as it limits the operational current density of the electrolyzer and is hence responsible for the fact that alkaline electrolyzers are so 'bulky'.

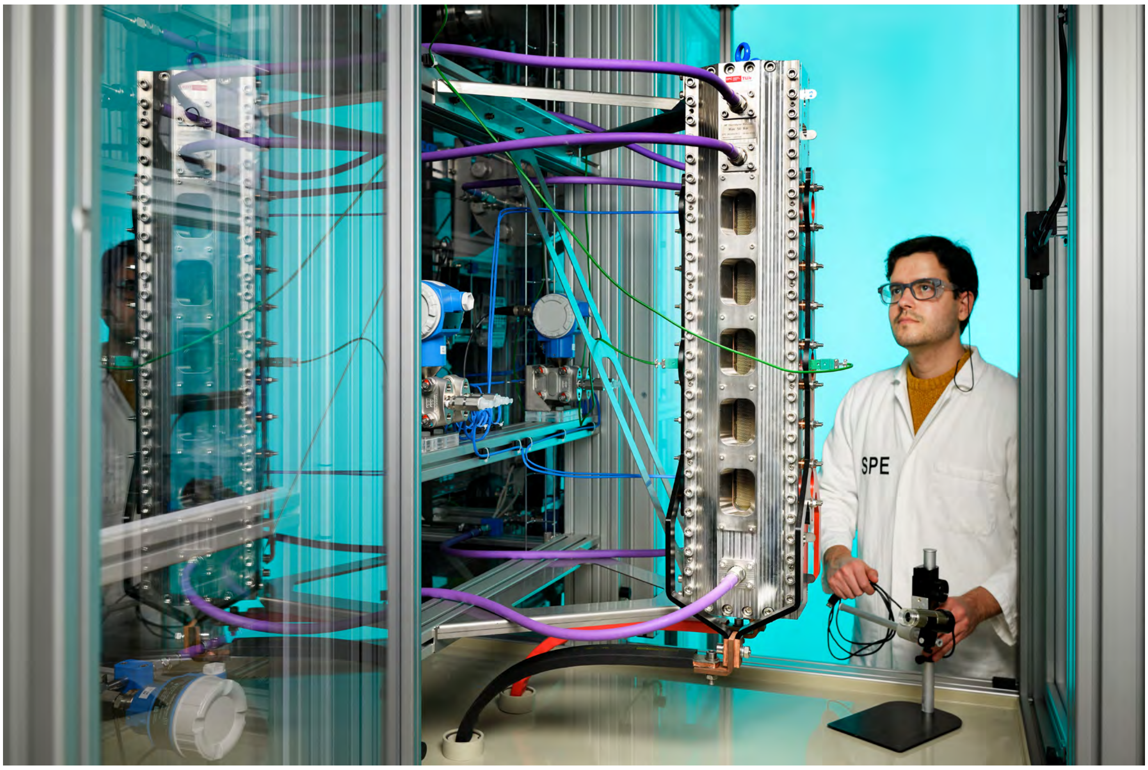


Figure 1: Alkaliboost setup: the ability to study alkaline electrolysis up to 90 °C and 50 bar.

In the Alkaliboost project, we are studying this ohmic resistance ‘mystery’ to find its origin. For this, we combine advanced electrochemical techniques such as electrochemical impedance spectroscopy with optical techniques, which allows us to study bubble behavior. We use 3D-printed electrolyzers, enabling us to study different cell configurations, and have a larger pressurized cell capable of operating up to 90 °C (see photo), enabling us to work under industrially relevant conditions and at a relevant scale. We combine this with advanced modeling techniques of multi-phase flows to enhance our physical understanding of the processes occurring in the electrolyzer.

The results of the Alkaliboost project suggest that gas bubbles play a key role. As expected, their presence in the electrolyte increases the ohmic resistance, but this effect seems less than expected. What seems especially relevant is the ability of the bubbles to stick to the separator or even form inside the separator as a result of supersaturation. This suggests that the hydrophilicity of the separator is of key importance and that increased hydrophilicity is the key to reducing ohmic resistance.
The Alkaliboost project is clearly of a multidisciplinary nature in electrochemical engineering, making it very suitable for collaboration within EIRES. This starts with colleagues from the field of electrochemistry, ranging from fundamental electrochemistry to electrocatalysis and porous electrodes. There are then specialists from related chemical engineering fields, such as materials science, thermodynamics, fluid dynamics, multi-phase flow, chemical reactor engineering and membranes. It even extends to the optimal integration of the electrochemical stack in the overall process. A good example of this is research that we have recently carried out on the interplay between the rectifier and the electrolyzer.

Societal impact

The results of the Alkaliboost project open the way towards alkaline electrolyzers with lower ohmic resistances that can be operated at higher current densities. This will enable the realization of more compact alkaline electrolyzers that need less raw material and will hence be significantly cheaper. This is of key importance to reducing the costs of green hydrogen and, in this way, accelerating the energy transition. The water electrolysis industry is expected to be worth over €1 T by 2050 and it is therefore not surprising that there is a large interest in the Alkaliboost project from the manufacturing industry. This interest ranges from electrode and separator suppliers to stack and system suppliers and end-users of the technology.

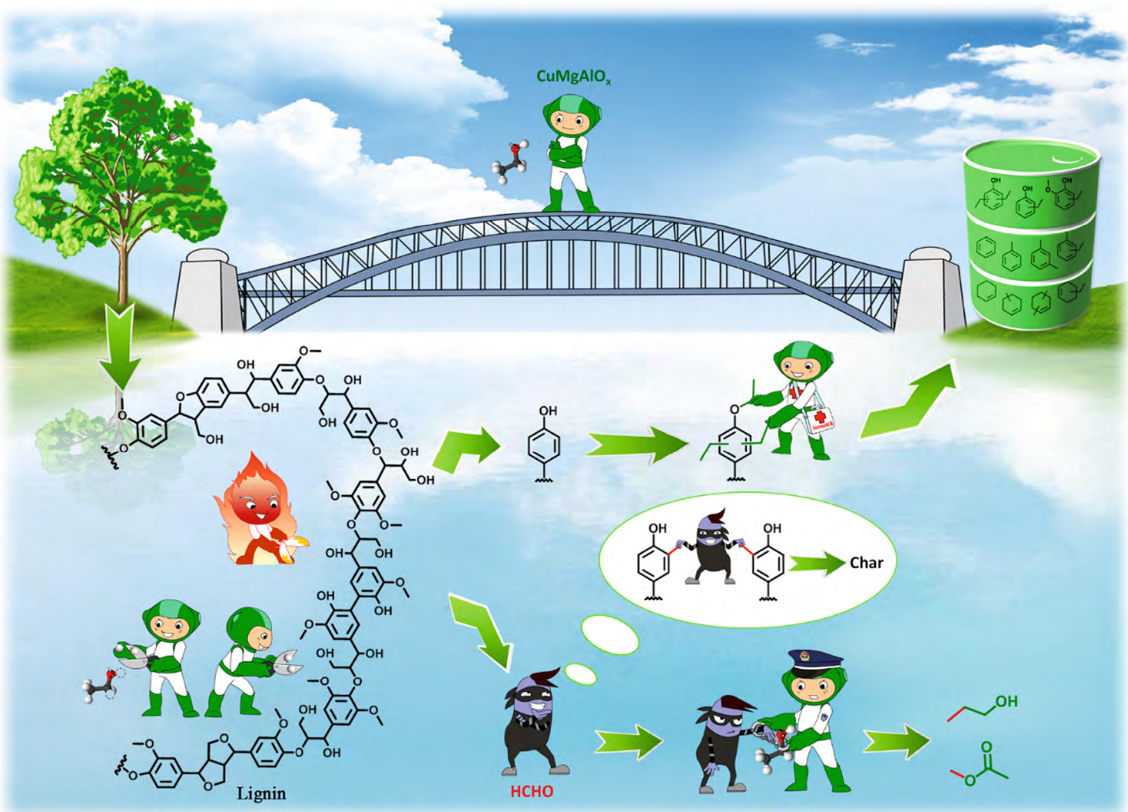
B.4. THE STORY OF VERTORO: BIOMASS VALORIZATION FROM IDEA TO VALUE

Context

Concerns about climate change are driving the replacement of fossil feedstock with renewable feedstock for the manufacture of chemicals and fuels. The use of lignocellulosic biomass instead of petroleum oil will significantly reduce the carbon footprint of the chemical industry. In the last decade, the Inorganic Chemistry and Catalysis (IMC) group has started a new research line in the field of carbohydrate and lignin conversion, which was initially strongly linked to the national SmartMix program CatchBio. The valorization of the lignin part of biomass is extremely challenging due to the recalcitrance of its polyphenolic network. Yet adding value to this fraction of plant-based biomass is crucial to rendering chemical conversion processes based on second-generation biomass profitable.

Our research

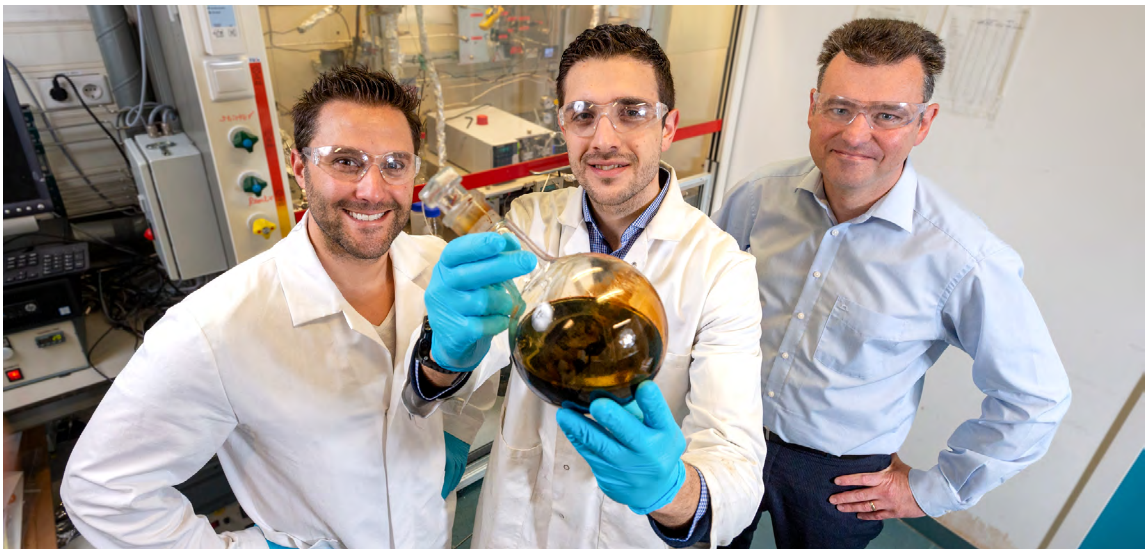
In 2010, the IMC group started a collaboration with the Combustion Technology group of the Department of Mechanical Engineering of TU/e within the framework of the PhD project of Michael Boot. Michael demonstrated the benefit of oxygenated aromatics for improving diesel engine efficiency and reducing soot emissions. This was the starting point for a fruitful collaboration aimed at overcoming the adage "one can make anything from lignin except money." Amongst other things, the research led to novel catalytic solvolysis chemistry, enabling the complete solubilization of lignin into mainly aromatic monomers (see Figure 1). Based on these promising results, the group started a pilot program within Chemelot InSciTe, the technical validation institute of TU/e, Maastricht University, DSM and Brightlands Chemelot Campus. In the Lignin RICHES project (2015-2020), PhD student Panos Kouris optimized alcohol solvolysis



technology with respect to feedstock diversity, product yield and economic profitability in close collaboration with experts from industry.

Societal impact

In 2017, the ambitious goal of this project to realize the world's first bio-refinery for lignin came a step closer. A first patent application was submitted and Vertoro, with Michael Boot as CEO and Panos Kouris as CTO, was founded along with an investment decision to construct a barrel-per-day pilot plant for the production of crude lignin oil (CLO). The rationale behind the patented CLO approach is to reduce the process severity and complexity such that solid lignin or lignin contained in lignocellulosic feedstock is converted into an oil which is amenable to further (catalytic) conversion to fuels and chemicals without consuming solvent and using supercritical temperatures (WO2019053287). A second patent application dealt with the upgrading of more abundantly available lignocellulose to a lignin-rich oil (WO2021064047). Along these lines, downstream processing patent applications were also filed, covering knowledge on the production of phenol (WO2019177458), alkylaromatics (WO2020234369) and heavy fuel oil (patent yet to be published). The close collaboration between the IMC group, Vertoro and InScitTe led not only to new knowledge protected by patents but also to high-impact publications in international scientific journals and new research lines and funding (national and EU Horizon 2020) aimed at marine fuel applications and specific chemicals from the different CLO fractions. The availability of kg-scale samples using pilot-scale batch facilities has already attracted broad interest in what is now called the *Goldilocks* technology of commercial partners from the energy and chemical sectors. Most prominently, this led to an offtake agreement and substantial investment from shipping giant Maersk in 2021. The Dutch investment company SHIFT Invest provided additional funding, resulting in a total capitalization of nearly €10 M for Vertoro, which will be mainly used to construct a 1 kiloton-per-annum continuous demo plant. This plant will be realized at the Brightlands Chemelot Campus alongside the already running pilot batch reactor. The demo plant is set to be commissioned in August 2022 and will provide the necessary input for the design of the first commercial plant (aim: 10 kton/annum in 2025). The short-term impact of this technology will be on sustainable shipping fuels, while there are also many opportunities to convert *Goldilocks* into biobased chemicals for producing aviation fuels, polymers and construction materials with a much-reduced carbon footprint. As such, the story of Vertoro is exemplary of intensive collaborations between academia and industry that overcome the innovation valley of death between research and successful innovation.



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