



# Research Report

## Chemical Engineering and Biotechnology, 2015-2020

Summaries and Case Studies

## Summary Chemical Engineering

The department of Chemical Engineering has an intentional breadth in disciplines, combining the chemical engineering core-expertise of designing chemical processes and reactors with related fields in materials science, chemistry and physics. We believe that this integrated approach puts us in an excellent position to address grand societal problems. Accordingly, we train chemical engineers to prepare themselves for the challenges of the coming decades.

In the coming years we will focus on addressing three emerging societal challenges: Circularity, Energy transition and Health engineering. The interests of our PIs are evenly distributed over these themes, which allows us to lead and participate in mission driven programs in these areas. Due to the rich variety of disciplines in our department allows us to effectively address the more complex engineering challenges, and create solutions which allow for industrial implementation. At the same time, a focused research plan will allow us to make more conscious decisions regarding the allocation of time and resources. The maintenance of our disciplinary strength in chemistry, chemical engineering and materials science will remain key to achieve our goals.

In order to improve our relation with industry we will make a plan with TU Delft Innovation & Impact Centre (IIC) to educate researchers about the possibilities of valorisation, the need for IP protection and licensing and the setting up spin-offs. To ensure proper matchmaking a more intensive mapping of what the department/faculty has to offer is aimed for.

Working in large, mission driven programs requires a strongly collaborative culture. The department will support behaviour that balances personal exposure with a sense for the greater good of e.g. our success in addressing a societal challenge. PIs, however, retain their independence in choosing the research direction of their choice. The subdivision of the department in sections is largely for administrative purposes, and the associated responsibilities will be clearly communicated.

While keeping the overall size of the department constant, we aim to rejuvenate our staff by hiring on average 1 Tenure Track candidate per year. In the past five years, we have increased the amount of PI's with an engineering background. In the coming years we will look more closely at the exact background of the candidates to align them with the disciplinary and organisational qualities needed to support the strategic choices of the department. To improve work-life balance and at the same time research and teaching quality, we aim to simplify our internal processes and to evaluate the balance between added value and time invested more carefully.

In the past years we have experienced the benefit of having a more diverse scientific staff. We strive to further improve the gender balance of our staff in such a way that it becomes equal to that of the graduates in our Chemical Engineering program (~30%). The increased diversity in our department calls for more attention to aspects related to social security and we will start a program to improve our awareness of this issue.

Finally, the department needs to define its position regarding open data and open science. While we subscribe to the latter, we should clarify how to implement that at the start of the project, especially in case of industrial funding. Regarding open data the department supports the development of a Digital Catalysis Lab (DCL) offering innovative instrumentation for high-throughput catalyst screening with the aid of robotics aiming for open, accessible data on catalytic processes. Regarding the accessibility of research data the department continues its search for a good digital lab journal, and will develop a policy on which data is relevant for storage and for what period.



# Case Study Chemical Engineering

## Case study e-Refinery

### History and background of e-Refinery

The past 5 years, the research scope of the Chemical Engineering department (ChemE) of the Faculty of Applied Sciences provided the opportunity to embark on more thematically oriented research programs. Large, collaborative research programs enable researchers to advance challenging, cross-disciplinary collaborations that allow for the development of new, complex systems and devices, and to develop strategic collaboration with other departments, universities and industries. Such programs capitalize on the fundamental strength of Chemical Engineering to combine chemistry of materials with chemical engineering.

Finding a program to rally around was not an easy task, and bottom-up initiatives of several PIs in the direction of energy storage and solar PV sadly failed to gain traction. However, in the course of 2016 the topic of e-Refinery materialized in one of the strategic, cross-faculty discussions on the challenges of the energy transition. It is based on the insight that the required reduction in CO<sub>2</sub> emissions in the (chemical) industry requires not only electrification of processes but also de-fossilisation of feedstock. This topic aligns particularly well with TU Delfts' ability to investigate complex interactions across multiple time (nanosecond-hours) and length (nanometer-meter) scales (Figure A1).

### Scientific vision and focus

While the electrification of the process industry covers a wide range of topics, the e-Refinery program focuses on the conversion of electrons to chemical bonds, which is needed to realize the required de-fossilisation of fuels and feedstock.

This e-Refinery scope encompasses the electrolysis of water, CO<sub>2</sub> and N<sub>2</sub>. We distinguish two pathways: direct and indirect conversion. The latter refers to the use of green (electrochemically produced) hydrogen which is to be integrated with thermochemical processes, e.g. to produce NH<sub>3</sub> from N<sub>2</sub> or CH<sub>4</sub> from CO<sub>2</sub>. The intermittent nature of sustainable electricity requires new designs for both the electrochemical as well as the thermochemical processes in order to achieve an optimal integration. The direct conversion of CO<sub>2</sub> and N<sub>2</sub> to base chemicals is a relatively new field, where the international focus is mainly on the nature of the catalytic process. In contrast, from the start the e-Refinery program has taken a systems approach with large scale employment in mind. This implies operation at high current densities and the use of widely available materials.



**Base Chemicals & Fuels**  
CO, HCOOH, C<sub>2</sub>H<sub>4</sub>, NH<sub>3</sub>, CH<sub>4</sub>,  
CH<sub>3</sub>OH, CH<sub>5</sub>OH, C<sub>4</sub>, C<sub>6</sub>.....

Figure A1: Overview of the disciplinary cohesion within the e-Refinery program





The mission of the e-Refinery program is to enable *and* to accelerate the implementation of electroconversion technology on an industrial scale. Accordingly, e-Refinery investigates complete conversion systems in order to analyse the fundamental limitations of these processes, applying the wide range of expertise available at the Delft Campus (see Figure A1).

### University support and collaboration

In 2020, the university granted the e-Refinery program the status of institute. The program is supported by five faculties: Applied Sciences (AS), Aerospace Engineering (AE), Mechanical, Maritime and Materials Engineering (3mE), Electrical Engineering, Mathematics & Computer Science (EEMCS) and Technology Policy and Management (TPM). Establishing collaborations between the available disciplines, which range from molecular interactions to catalysis, transport phenomena, reactor design, and process control to system design and industrial integration, is challenging. Nevertheless, large cross-disciplinary projects are currently running, funded via either NWO Perspectief, NWO cross-over program, TKI-funds or EU-streams, and each of these projects includes multiple faculties within TU Delft. Additionally, in pre-COVID times, several exchanges with around thirty PIs and industrial representatives were organised.

In COVID times the interaction mainly takes the form of two, monthly online colloquia (attended by ~100 persons) and topical meetings on topics such as membrane development, safety and e-Refinery's 100kW upscaling plan. e-Refinery operates as an umbrella organisation, providing support for cross-disciplinary research projects and help in community building. Since the energy transition requires the energy, transport and industrial sectors to come together, a network was established that involves them all (e.g. Shell, Vattenfall, Rotterdam harbour).

In doing so, the e-Refinery program has been very successful in acquiring funding for cross-faculty and (inter-)national programs of around 40 MEuro in total. Approximately 25 MEuro of this funding has landed at TU Delft and a fair fraction of that was obtained by ChemE.

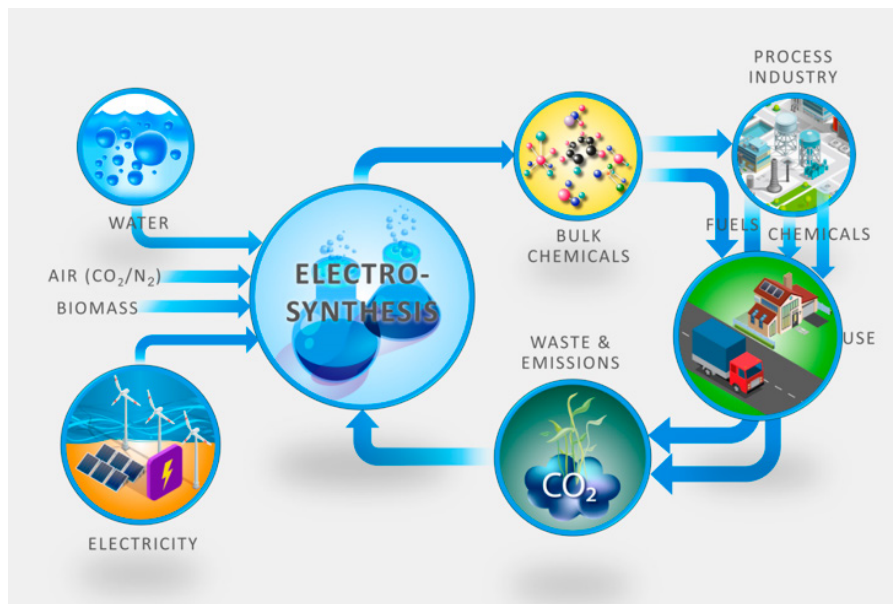


Figure A2: Overview of the e-Refinery program concept



Figure A3: Snapshot of industrial parties collaborating in projects of the e-refinery institute

More importantly, the increased collaboration with our sister departments at various faculties has led to an increased number of joint master theses, joint publications, and more interaction with industry (Figure A3). The latter is highly productive, since we can thereby help shape the industrial vision of the energy transition, while industry advises us on the challenges they perceive in the energy transition.

### Future perspectives

The overarching aim of the e-Refinery program is to find generalized rules for the design of electrochemical conversion processes, based on the nature of the feed and the intended product. To achieve this goal, e-Refinery addresses the fundamental questions related to performance, design, and scaling in the (thermo-)electrochemical process of a few simple base products.



For funding we will use the various mission driven opportunities as presented by e.g. the GroenvermogenNL initiative (a Dutch private-public funded collaboration aiming for competitive hydrogen production, storage and renewable refining of C-based products) and the Climate Action initiative of TU Delft (providing 16 TUD-funded tenure trackers on e.g. negative emissions and circular economy). For the techno-economic assessment of new, e-Refinery-based technology, complete systems up to a ~100 kW scale are needed. The appropriate funding resources for this scale will be a challenge to the commitment of industry, government and university alike. Its benefits, however, will not be limited to research and development; this lab would also be a fantastic tool to integrate the challenges of the energy transition for the chemical industry in our educational programs.

### Highlighted ChemE publications within e-Refinery

1. WA Smith, T Burdyny, DA Vermaas, H Geerlings, *Pathways to industrial-scale fuel out of thin air from CO<sub>2</sub> electrolysis*, Joule 3 (8), 1822-1834
2. Ludovic Jourdin, Thomas Burdyny, *Microbial Electrosynthesis: Where Do We Go from Here?*, Trends in Biotechnology 39, 2021, 359-369,
3. Divya Bohra, Jehanzeb H. Chaudhry, Thomas Burdyny, Evgeny A. Pidko and Wilson A. Smith *Modeling the electrical double layer to understand the reaction environment in a CO<sub>2</sub> electrocatalytic system*, Energy Environ. Sci., 2019,12, 3380-3389
4. FM Mulder, BMH Weninger, J Middelkoop, FGB Ooms, H Schreuders, *Efficient electricity storage with a battolyser, an integrated Ni-Fe battery and electrolyser*, Energy & Environmental Science 10 (3), 756-764
5. R Zaffaroni, D Ripepi, J Middelkoop, FM Mulder, *Gas Chromatographic Method for In Situ Ammonia Quantification at Parts per Billion Levels*, ACS Energy Letters 5 (12), 3773-377
6. MA Blommaert, JAH Verdonk, HCB Blommaert, WA Smith, DA Vermaas, *Reduced Ion Crossover in Bipolar Membrane Electrolysis via Increased Current Density, Molecular Size, and Valence*, ACS Applied Energy Materials 3 (6), 5804-5812
7. J Luo, DA Vermaas, D Bi, A Hagfeldt, WA Smith, M Grätzel, *Bipolar membrane-assisted solar water splitting in optimal pH*, Advanced Energy Materials 6 (13), 1600100



## Summary Biotechnology

The department of Biotechnology aims to contribute to the transition to a sustainable, low-emission society by integrating application-inspired, fundamental research with design and engineering. Together, our team of principal investigators (PI's) cover all relevant levels of organization in biotechnological processes: discovery, characterization, and engineering of enzymes as molecular catalysts; physiology, systems biology and engineering of microbial cells and cellular networks; ecophysiology of microbial populations; design and integration of unit operations in industrial and environmental bioprocesses and analysis of the socio-economic impacts of technological innovations.

The reporting period 2015-2020 was productive in terms of ground-breaking science as well as industrial and societal implementation of our research, while 93 PhD of our alumni continued their careers in industry (over 50%), academia (25%) or elsewhere. At the organization level, we effected a shift from hierarchical research groups to an inclusive 'teams' model. Our five research sections now serve as thematic, organizational and social clusters that support independence and visibility of individual PI's. Dynamics in our staff and national Sectorplan funding enabled us to recruit 11 new tenure-track assistant professors who contribute to our shared mission by exploring new research lines. In addition, we were able to make substantial investments in our research infrastructure.

In the coming years, we will continue to invest in our strengths in industrial biotechnology (including microbial biotechnology and enzyme-based biocatalysis) and environmental biotechnology, while intensifying research on health-related aspects of biotechnology. In doing so, we will further exploit the potential of our interdisciplinary team for jointly taking on scientifically challenging and societally relevant themes such as zero-emission biotechnology and green chemistry, circular biotechnological processes and sustainable microbial production of food ingredients.

Key objectives for the coming period include:

- Further strengthen internal collaboration around challenging and societally relevant themes by joint participation of PI's in large projects.
- Start programme on the topic 'zero-emission biotechnology' involving all our tenure-track assistant professors. Centred around 12 PhD positions funded by our department, this programme aims to attract additional public and private funding.
- Implement the large, open UNLOCK facility for exploration of microbial diversity in controlled bioreactor set-ups (collaboration with Wageningen University).
- After a period in which personnel dynamics forced our PI's to devote more attention to internal organization, reinforce our contribution to shaping (inter)national research agendas.
- Strengthen our capabilities in computational biotechnology by recruitment of a new tenure-track assistant professor and by intensifying collaboration with specialists at the Faculty of Electrical Engineering, Mathematics & Computer Science.
- Foster a culture in which the objective of finishing a PhD project within the 4-year contract term, as agreed upon by all our PI's, is internalized and actively pursued by all supervisors and PhD students.
- In addition to consolidating gender balance of our team, we will also strive to improve diversity along other axes.
- Improve work-life balance, especially of our technical support staff, by critically evaluating internal processes, acquiring funds for project-associated support staff and minimizing impacts of externally imposed administrative procedures on workload.



# Case Study Biotechnology

## Case study: Kaumera

### History and background of Kaumera

Kaumera was discovered by researchers from the Department of Biotechnology (BT) of the Faculty of Applied Sciences, TU Delft. It is a new type of biobased raw material with a wide range of properties that can be extracted from the sludge granules that form during a wastewater purification process. Kaumera means “chameleon” in Maori, the language of the original inhabitants of New Zealand, and was adopted to reflect the versatility of the material.

The discovery of [Kaumera](#) emerged from the development of another highly successful technology: [Nereda®](#), which also originated from Mark van Loosdrecht and his colleagues. Nereda® is a sustainable wastewater treatment bioprocess technology for municipal and industrial water. It stimulates micro-organisms to form granular biofilms (called “granules”) rather than the traditional flocs in the water treatment process. As a result, the sludge settles much more rapidly, allowing a substantial process intensification. The purification efficiency of this technology is very high, it needs 70 % less space, it uses relatively little energy and the economic costs are lower. Nereda® has been quickly commercialized since 2012. Currently (2021), there are more than 78 Nereda® sewage treatment plants in operation or under construction all over the world.

The most unique and important property of granular sludge is the high amount of hydrogel-like extracellular biopolymers produced by the microorganisms. These polymers form a matrix in which the microorganisms are self-immobilized. The development of Nereda® drove the curiosity to investigate what these biopolymers are. With her Marie-Curie individual fellowship, Yuemei Lin joined BT as a post-doc working on this research topic. This led to the development of Kaumera. TU Delft encourages exceptional female academic researchers to pursue their career and supported by the Delft Technology fellowship Yuemei was appointed as tenure track assistant professor in 2014 to fully develop this research line.

At the same time, a public-private partnership called the National Kaumera Development Programme (NKOP) was established in 2013. In this programme, Delft University of Technology, the Vallei and Veluwe Water Authority, Rijn en IJssel Water Authority, the Dutch Foundation for Applied Research in Water Management (STOWA),

Chaincraft bv, and Royal HaskoningDHV engineering consultancy work closely together, focusing on lab research and pilot experiments for Kaumera production. This collaboration resulted in the opening of the world's first Kaumera extraction factory in 2019 in Zutphen, and the first commercial delivery of Kaumera for use as a binder and biostimulant material in 2021.

### Scientific interest and collaboration

A significant amount of Kaumera can be recovered from Nereda® sludge (about 20-35% of the granular sludge dry weight). Kaumera mainly consists of biopolymers that are produced by bacteria to form the granular sludge. These are generically called extracellular polymeric substances (EPS). EPS is responsible for the chemical and physical properties of biofilms (including granular sludge). Due to its extraordinary complexity, EPS is considered a “black box”. Only a few aspects of the biopolymer are reasonably well understood. Its structure and property are still not fully understood, and this type of biopolymer has not been previously exploited as a renewable bio-based material. The development of the Kaumera research line has gradually opened up the “black box” of EPS, resulting in the discovery of new components and new functionalities.

At an earlier stage, support from both the Delft Technology fellowship and the Soehngen Institute of Anaerobic Microbiology (SIAM) programme (Gravitation programme of the Netherlands Organisation for Scientific Research (NWO)) made it possible to hire three PhDs (Simon Felz, Marissa Boleij and Hugo Kleikamp) with the focus on setting up methodologies for EPS characterization. Thanks to the close collaborations between PI's, the involvement of Martin Pabst together with the strong analytical platform in BT, boosted the research of protein glycosylation through mass spectrometry. New components, such as sialic acids and sulphated glycoconjugates, which were not expected to be produced by environmental microorganisms, have been discovered in Kaumera. In addition, the expertise of David Weissbrodt has allowed the study of the metabolic pathways of Kaumera components (PhD project of Sergio Thomas Martinez). These studies raise the scientific question about why EPS is so complex and how, for instance, sialic acids are involved, as these were mainly seen as cell recognition molecules in multicellular organisms until now.







Figure 3. The Nereda® plant and the Kaumera factory in Zutphen, The Netherlands.

The gradually revealed chemical structure of Kaumera stimulates further scientific thinking: how to use sustainable biopolymers to produce high performance new materials and composites. This drives various research collaborations on Kaumera-based new material within TU Delft, in the Netherlands and internationally.

Besides the investigation of the polymer physics of Kaumera, Stephen Picken and his team (Jure Zlopasa, Suellen Espindola and Anand Raja) at TU Delft's Department of Chemical Engineering are developing high performance Kaumera based bio(nano)composites, light weight foams, and superabsorbents. Great progress has been made in Kaumera-based biocomposites which have unusually high stiffness, outperforming many synthetic composite materials. In addition to the intensive collaboration with ChemE, Claire Chassagne from the Faculty of Civil Engineering and Geosciences studies Kaumera as a flocculant, and Hanieh Bazyar from the Faculty of Mechanical, Maritime and Materials Engineering is making Kaumera-based membranes. In addition, a Kaumera-cellulose composite is being developed within the Amsterdam Institute for Advanced Metropolitan Solutions (Peter Mooij). It is low-weight and has a comparable strength and stiffness to frequently used building and construction materials. The interesting flame retardant property of Kaumera are being studied in collaboration with Nam Kim at the Advanced Composite Center, University of Auckland, New Zealand.

Over the last six years, a number of Kaumera related research projects were granted. To name a few: the COMPRO project "Converting Wastewater into Composites", NWO Closed cycles-transition to a circular economy project "Nature inspired biopolymer nanocomposites towards a cyclic economy (Nanocycle)" (2 PhDs), and a TKI project "Kaumera development" (2 PhDs). The market exploration of Kaumera has become part of the TU Delft/BT led EU project "WATER MINING" (17 million). Moreover, an international EPS research community has been founded and EPS workshops were co-organized by Yuemei Lin at various international conferences.

The activities between the Biotechnology and Chemical Engineering departments on biopolymers result in intellectual property and potential new spin-off companies. New business development related to biopolymers is coordinated through [Slimy Green Stuff](#), a separate company under the TU Delft holding.

### Societal impact and collaboration

The transition towards a more resource-efficient society is a core goal of European governments, and indeed worldwide. Converting waste into valuable resources is at the heart of a circular economy. The Kaumera projects show that this is not only possible, but also economically feasible. Currently, the sludge produced from wastewater, including the granular sludge, is still considered waste. Sludge disposal is a significant fraction of treatment costs (up to 30%). The large production of Kaumera (20-35% of waste sludge dry weight) provides an economic incentive to develop new applications and products. The current hydrogel market is largely supply limited and prices are relative high, while the volume of Kaumera produced in current Nereda installations would generate the same market volume as that of e.g. alginate, which is one of the larger bio-based hydrocolloid polymer markets. It is worth noting that the per capita production of Kaumera could amount to about 20% of the synthetic polymer production and use (10 kg of Kaumera per capita/year, versus about 50 kg of all synthetic polymers per capita/year).

The Nereda® process is sustainable, cost efficient and helps to improve sanitation. Moreover, Kaumera recovered from the Nereda® granules is a potentially valuable substitute for many fossil fuel based chemicals that find their application in numerous industries: currently e.g. as a seed coating to replace non-biodegradable synthetic polymers, and in the longer run as a high-strength and non-flammable bio-composite material in the field of building and construction. On top of this, by removing Kaumera from the purified sludge, 20-35% less sludge has to be removed and disposed of.





This has a substantial positive effect on the energy consumption and CO<sub>2</sub> footprint. It is anticipated that a commercial Kaumera production can be established which would offset the wastewater treatment costs, thereby stimulating easier introduction of wastewater treatment in areas where such facilities are currently absent for economic reasons.

From the very early stage, a public-private partnership played an important role. Within the National Kaumera Development Programme (NKOP – organised analogues to the successful National Nereda Development Programme), all parties contribute knowledge and expertise needed to recover, process and market the new raw Kaumera material. In this way, the Water Authorities, the scientific community and the business community work together on a sustainable, circular economy. The Kaumera development is made possible in part by subsidies from the European Union (LIFE), the Ministry of Economic Affairs and Climate Policy and the Province of Gelderland, the cooperation of Friesland Campina and the Dutch Water Authorities. With all these forces joined together, two demo plants have been put in operation: the first factory is located in Zutphen, near the Rijn en IJssel Water Authority and has been producing Kaumera from the process water of the dairy industry since October 2019. A second plant in Epe near the Vallei en Veluwe Water Authority now also produces Kaumera from sewage water treatment, mainly from households.

### Future perspectives

In the coming 5 years, researchers at BT will continue to unravel the exact molecular structure of Kaumera by studying its physical-chemical properties, elucidating its full metabolic pathways and manipulating its production. Further scaling-up of Kaumera will be achieved via the WATER MINING project to allow it to be incorporated into different industries in several EU countries. In parallel, Kaumera-based products are being developed and brought to the market with the continued support from industry and water boards, and in close collaboration with ChemE and other departments at TU Delft. The research on Kaumera will also lead to the development of new start-up companies, with products such as Kaumera-based superabsorbents, sialic acids, and sulfated glycoconjugates for medical applications.



