university of groningen

Green Industry Innovation Agenda

Industry Relations
Connecting to society

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Aim of this Innovation Agenda

The University of Groningen stimulates interdisciplinary research and facilitates a unique environment for collaboration between different fields of expertise and external partners. With this innovation agenda, we intend to present our research carried out in the **Green Industry** theme, as well as current collaborations and our ambitions for future joint projects with relevant stakeholders. We invite companies, nonprofit organizations and governmental organizations to contact us (via *industryrelations@rug.nl*) and explore opportunities to connect, find synergies and together contribute to the development of the green industries of the future.

What is a Green Industry?

While the term green industry cannot fall into a single definition, it is well-accepted as an economic activity that strives to minimize and mitigate its environmental impacts. This can be achieved by highly efficient and integrated production processes, in line with societal needs and governmental regulations. Typically, the following characteristics apply to green industries:

- → Production processes with minimal use of water, energy and materials;
- → Sustainably obtained feedstocks (biobased);
- → Powered by renewable, decarbonized energy systems (*i.e.* wind, solar);
- → Maximal reuse and recycling of streams;
- → Strongly integrated and optimized processes;
- → Substantially lower emissions, effluents and greenhouse gases;
- → Products built for longevity and durability.

The Northern Netherlands is actively building on the green industries of the future by stimulating economic activities, enabling the creation (and retention) of jobs as well as providing a concrete contribution to the Netherlands' climate objectives and circular economy[1]. Accordingly, one of the main goals of the Dutch climate agreement is to reduce the emission of greenhouse gases by 49% in 2030 and by 100% in 2050[2], in line with the Paris climate agreement signed by 195 countries to keep global warming well below 2 ^{o}C. Further objectives involve the achievement of a zero emission mobility system, climate neutral agriculture and fully circular industrial sector.
The current efforts and ambitions of the University of Groningen aim to support these and other sustainable development goals[3] (such as economic prosperity; social inclusion, cohesion and justice; good governance) through (inter)disciplinary studies. Three main societal themes guide our research, namely *Energy*, *Healthy Ageing* and *Sustainable Society*[4], aiming to bridge the gap between science and society as well as address future challenges and opportunities.

[1] https://www.metabolic.nl/projects/noord-nederland-circulair

[2] https://www.klimaatakkoord.nl/documenten/publicaties/2019/06/28/klimaatakkoord

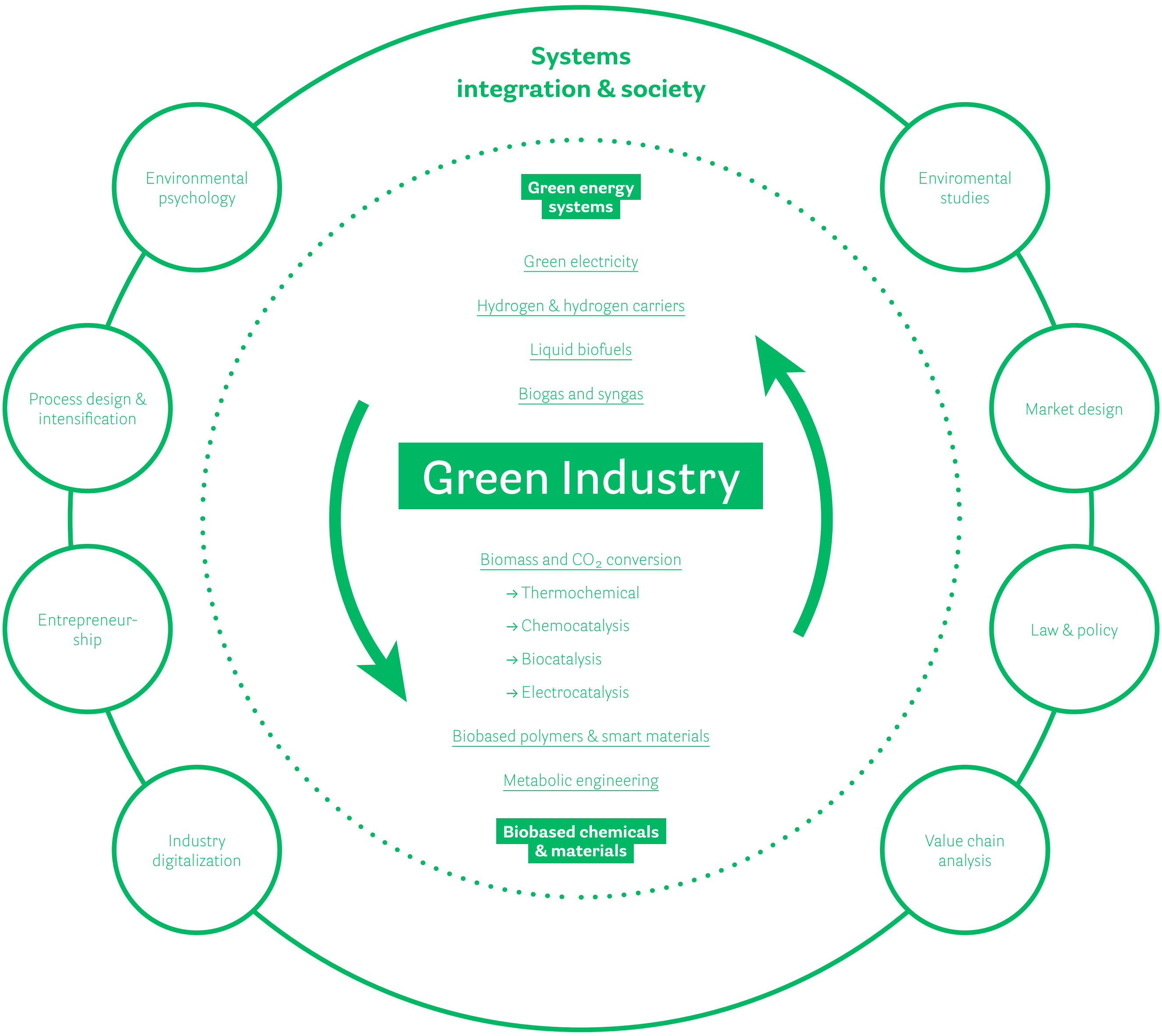
[3] https://sustainabledevelopment.un.org

[4] https://www.rug.nl/research/societal-themes

Green Industry Research at the University of Groningen

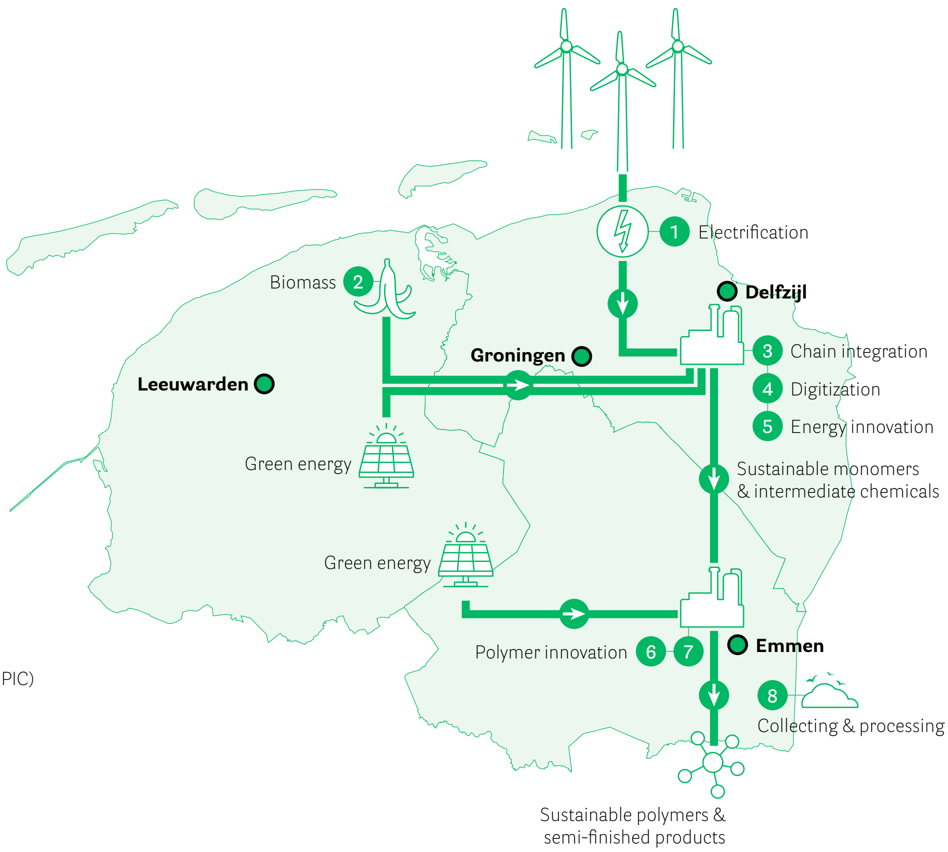
Under the Green Industry knowledge umbrella, the research being carried out at the University of Groningen covers a wide range of topics, as illustrated in Figure 1. Three main themes (**Green energy systems**, **Biobased chemicals & Materials** and **Systems integration & Society**) are proposed, as well as sub-themes that go from the technical and technological challenges of green industries (such as biomass valorization and green hydrogen) to their integration and interaction in our society (law & policy, value chain analysis, entrepreneurship).

Figure 1. Overview of the Green Industry Innovation Agenda themes and sub-themes



There are two main concepts that serve as general guidelines to our studies within the Green Industry theme: **Circularity** and **Sustainability**. Circular systems are regenerative systems in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops. This can be achieved through long-lasting design, maintenance, repair, reuse, remanufacturing, refurbishing, and recycling. The sustainability concept goes beyond the technosphere and can be defined as the balanced integration of economic performance, social inclusiveness and environmental resilience, supported by a legal framework to the benefit of current and future generations. Based on these concepts, this innovation agenda aims to support studies involving relevant stakeholders (*i.e.* companies, non-profit organizations, governments and citizens) to jointly share experience and knowledge, test and validate research hypotheses and perform pilots. Furthermore, we aim to bring together researchers from different areas of expertise and support interdisciplinary studies with great potential for implementation. Finally, the unique location of the University of Groningen creates great opportunities for the development of green industries, being a major knowledge institute within the innovative ecosystem of Northern Netherlands (Figure 2), well-connected with the Delfzijl and Emmen chemical clusters. Our Green Industry research ecosystem is well aligned with the regional focus themes[5], namely green raw materials, energy innovation, circular business models, digitalization and infrastructure.

Figure 2. Green Industry innovation ecosystem in Northern Netherlands[6]



1. MW Test Centre (Hydrohub)
2. Zernike Advanced Processing (ZAP)
3. Chemport Industry Campus
4. Smart Industry Hub
5. EnTranCe
6. Sustainable Polymer Innovation Cluster (SPIC)
7. Green PAC Polymer Application Centre
8. Kenniscentrum Recycling

[5] https://www.chemport.eu/wp-content/uploads/2020/01/Chemport-industrieagenda.pdf

[6] https://www.topdutch.com/invest/key-industries/green-chemistry

Participating Faculties

More than 90 researchers from the following faculties are involved in this innovation agenda (see page 37 for a detailed overview and contact list). The next sections will further detail the themes explored by our current research groups, as well as our ambitions for the future.

- → Faculty of Behavioral and Social Sciences (FBSS)
- → Faculty of Economics and Business (FEB)
- → Faculty of Law (Law)
- → Faculty of Science and Engineering (FSE)
- → Faculty of Spatial Sciences (FSS)
- → University College Groningen (UCG)
- → Campus Fryslân (CF)

Theme 1

1

Green Energy Systems

Introduction

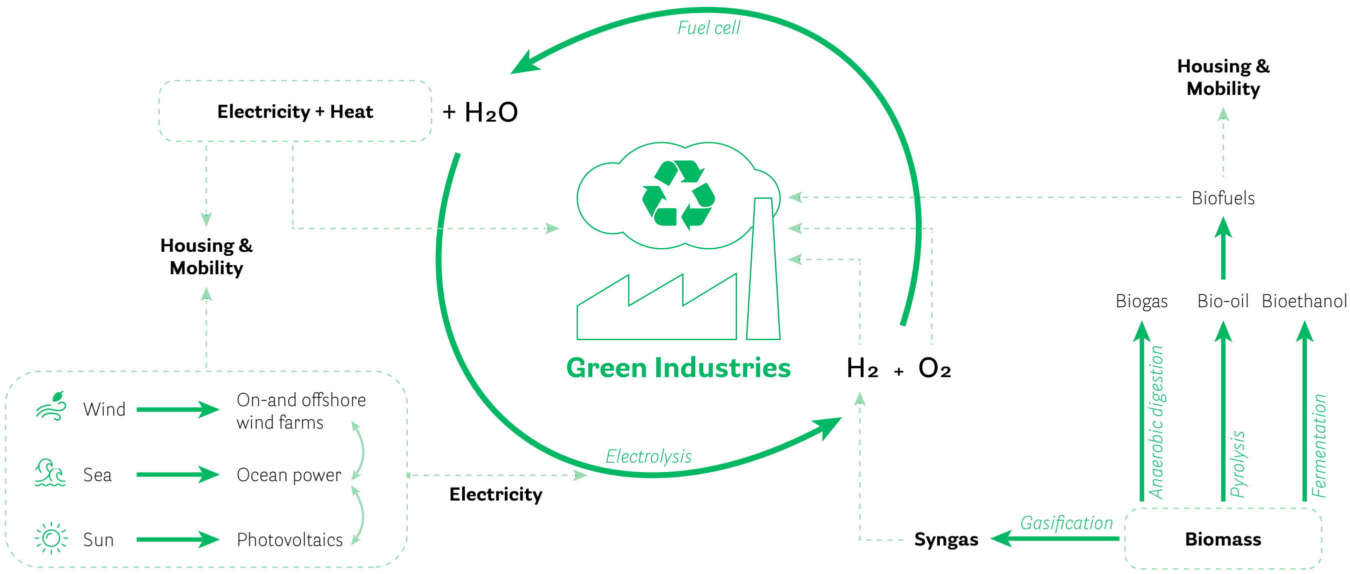
As the majority of the carbon emissions worldwide comes from the traditional fossil-based energy production systems, it is fundamental to develop green energy systems based on renewable sources and negative/neutral emission technologies. Our main ambitions in this field are summarized in the bullet points below.

Our ambitions

- → *Design efficient hybrid systems for harvesting energy from the wind and sea;*
- → *Develop advanced materials for photovoltaics, with higher efficiency and new applications;*
- → *Design a hydrogen-based economy in the context of Northern Netherlands, with green hydrogen as main energy carrier;*
- → *Develop strategies to efficiently convert biomass (particularly waste streams) into power, heat and energy-dense gaseous and liquid mixtures;*
- → *Design robust smart grids for the (decentralized) energy systems of the future, as well as their legal regulatory framework.*

Figure 3 illustrates the Green Energy Systems sub-themes as well as their synergy in the promising scenario promoted by the use of green and renewable resources for energy generation. Our current efforts in each of the sub-themes (**Green Electricity**, **Hydrogen as Energy Carrier** and **Energy from Biomass**) will be further detailed in the following sections. Throughout the text, references link specific information to the researcher(s) involved, and a list of contact points is provided in section 5 of this agenda.

Figure 3. Green Industry innovation ecosystem in Northern Netherlands



1.1. Green Electricity

Moving to green electricity is an important measure to decarbonize and therefore preserve our planet. In the Netherlands, gray energy is still the most supplied, coming mainly from natural gas and coal (>80% combined). In order to shift this scenario to a more sustainable one, technologies able to efficiently supply green electricity from the wind, the sun and the sea need to be further explored and developed.

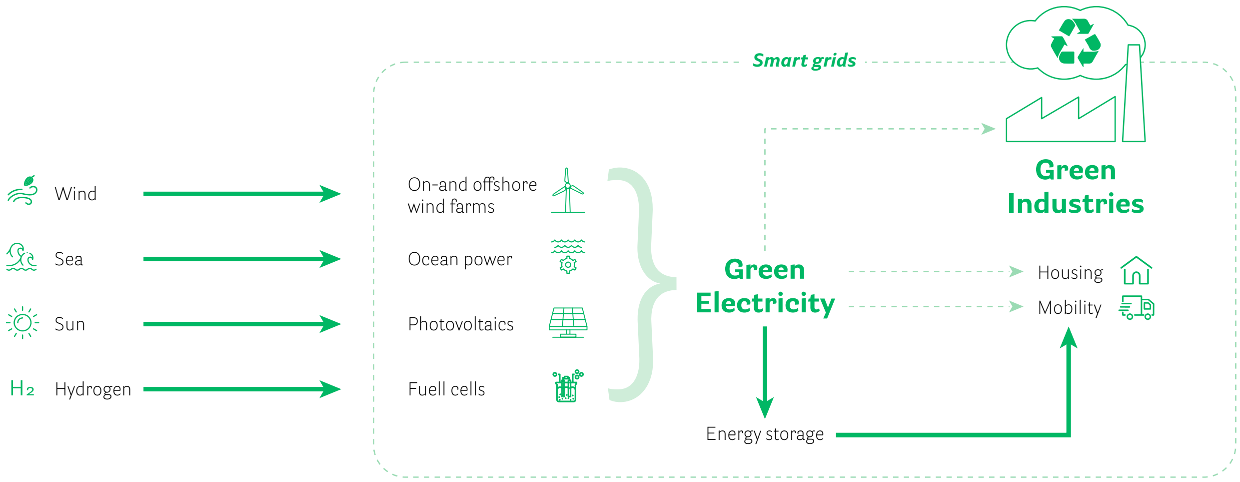
At the University of Groningen, extensive interdisciplinary research has been performed on topics related to green electricity, particularly wind energy due to the regional potential. For instance, in the field of advanced manufacturing and mechanical engineering, studies focusing on the harvest and storage of energy from sea waves and wind supported the creation of the start-up *Ocean Grazer*. [1, 2] This hybrid system produces renewable offshore energy by integrating three technologies developed in our laboratories, *i.e.* ocean battery, ocean foundation and ocean power (see section 9). Furthermore, the interesting concept of biomimetics, which is the use of nature as a model for technological developments, has been applied to design advanced wind turbines able to operate efficiently at low wind speeds. The so-called 'lift-enhancing periodic stall' principle, inspired in the wings of seabirds, recently received a European patent. This innovative technology caught a lot of interest from industry, leading to the formation of a consortium to bring the invention towards application in large wind turbines (*Albatrozz*, see section 9). [3] Our law researchers from the *GCELS* (*Groningen Centre of Energy Law and Sustainability*, see section 8) have been involved in the design of legal instruments to promote on- and offshore wind energy developments for more than a decade. Important consortia include, among others, the *PROMOTioN* H2020 project, focused on the development of offshore grids on the basis of cost-effective and reliable technological innovation in combination with a political, financial and legal regulatory framework; and the *Wind Energy on the North Sea Energy* NWO project, focused on the development of a general framework to identify relevant moral values and possible conflicts related to offshore wind energy in the North Sea. [4] A recently funded project within the *PhD@Sea* NWO program will analyze the feasibility of bringing large amounts of offshore wind energy to shore from a cross-disciplinary perspective. The planned research will be based on novel technologies and focus on the assessment of technical challenges, whilst also taking into account market, regulatory frameworks, new legal instruments and spatial planning considerations (see section 4). [1,2,4,5] Besides the technical, spatial and legal aspects of wind farms, logistics are an important aspect to be considered and optimized due to the high costs associated with it. With this purpose, a large research consortium led by the University of Groningen works on the optimization of service logistics in the context of offshore wind farms. Our researchers develop new concepts, models and tools which contribute to a significant reduction in logistic costs and bring a positive effect on sustainability as well. For instance, apart from the cost savings, improved maintenance planning and smarter logistics will help to reduce CO_2 emission and risks for maintenance staff. Important to mention, the outcomes of this research will be suitable for use in service logistics related to other sectors, as a major element of the project is the generalization and distribution of new insights and models to better incorporate sustainability within the decisions regarding logistics. [6,7]

In the field of solar energy, our expertise covers a broad range of technologies as well. The NWO Focus Group *Next generation organic photovoltaics* works on enabling the realization of the next generation of solution-processed organic photovoltaics (OPV) through a multidisciplinary approach in which physics, photophysics, device physics, organic chemistry, material science and theoretical modeling are combined synergistically to achieve a full understanding of the fundamental mechanisms of photo induced charge-separation. [8,9,10,11,12] Further in-depth research is carried out in the field of photophysics, optoelectronics and nanomaterials chemistry, where the properties of various semiconductor materials (such as hybrid perovskites, colloidal quantum dots, organic semiconductors and carbon nanotubes) are studied, aiming for applications in cheap and high performing solar cells (as well as other electronic devices) [9,10,13]. The University of Groningen also participates as an academic partner in the *Solliance Solar Research*, a joint venture of R&D organizations and industries working on the development of thin-film photovoltaic (PV) technologies. These flexible PV modules are based on perovskite, copper indium gallium selenide or cadmium telluride instead of silicon and have a wide range of possible applications (such as vehicles and building materials). [8]

Moving to energy storage and electrochemistry, batteries and fuel cells are also important topics tackled by our research groups from different perspectives, *i.e.* materials chemistry, catalysis and thermodynamics, aiming for the development of highly efficient bioenergy systems and emission negative technologies. [14,15,16,17,18] The storage of intermittent wind and solar energy presents a major challenge for a reliable green power grid in the future. Large-scale electrical energy storage in (redox-flow) batteries is attractive, but bringing down the levelized cost of storage is required. At the University of Groningen, innovative battery materials based on organic compounds that do not contain scarce/expensive elements are being developed. Such materials can provide cheap and readily available alternatives to current battery technologies (such as Li-ion and vanadium-based RFBs), and our research aims at the better understanding of their redox-chemistry, long-term stability and overall performance. [17] Moreover, the development of operable batteries, especially for large scale energy storage such as iron air batteries, needs real time characterization with spatial as well as temporal resolution. Our researchers have developed state of the art techniques based primarily on Raman spectroscopy and spectroelectrochemistry to tackle this challenge. [14,18] Fuel cell technology allows for the electrochemical conversion of the chemical energy of a fuel (often hydrogen) into electricity, and as the development of a green hydrogen economy is of particular interest for the region, the next dedicated section will explore it in detail. Important to mention, green electricity can be also used to promote thermodynamically unfavorable reactions for the conversion of CO_2 and biomass into valuable products. [15] Such promising electrochemical routes will be further detailed in section 2.1 of this agenda.

One remarkable challenge in bringing such energy technologies towards realization is their integration within the power grid. Accordingly, the so-called smart grids allow the combination of decentralized renewable energy resources, as well as the integration of energy production and consumption components, enabling an increased demand response and energy efficiency. New control strategies to guarantee a stable, efficient and safe operation of such grids are necessary, and this challenge has been addressed by our researchers in the field of smart energy systems. In detail, our current engineering research in the field of smart grids focuses on: new approaches for the modeling, analysis and control of smart grids based on energy functions; design challenges of future energy systems related to the mathematical models' complexity; solving decision-making problems of integrated energy systems; forecasting, planning and guaranteeing the stability of smart grids; optimization under uncertainty, data-driven methods, game theory and distributed algorithms in the context of smart grids. [2,19,20,21,22,23,24,25,26] Furthermore, our researchers from engineering and environmental psychology closely collaborate in various initiatives related to the development and acceptability of green energy systems. Some remarkable examples are the projects *ERSAS* (incentives and algorithms for efficient, reliable and socially acceptable energy system integration), *MERGE* (effective and acceptable energy management systems and user interfaces to match energy demand and supply), *MatchIT* (efficient demand and supply matching by incentivizing end-users in buildings) and *TOP-UP* (top-down energy projects as catalysts for bottom-up local energy initiatives, see section 4). Overall, these interdisciplinary frameworks incorporate our expertise in modelling, automation, financial and social incentives to successfully implement and optimize smart and green energy systems.[19,27,28] The legal research at the University of Groningen is also heavily focused on the transition towards smart energy systems, and our researchers participate in a wide range of projects such as *DISPATCH* (integration of demand-side management into the current electricity system by means of a flexibility market), *SmaRds* (development of an integrated regime that addresses behavioral uncertainties related to smart grids, *i.e.* the legal design of emerging organizational settings and the policy design of smart grid implementation in municipalities) and the *SMILE* (smart islands energy system) H2020 consortia, which addresses the development of nine smart grid solutions in three large-scale pilot projects in different regions of Europe with similar topographic characteristics but different policies. Accordingly, the goal of this interdisciplinary project is to foster the market introduction of these technologies, and its legal perspective involves energy storage, power to heat, microgrids and local grid regulation issues, both at EU and national levels. [4,29]

Figure 4. Green electricity in the context of green industries



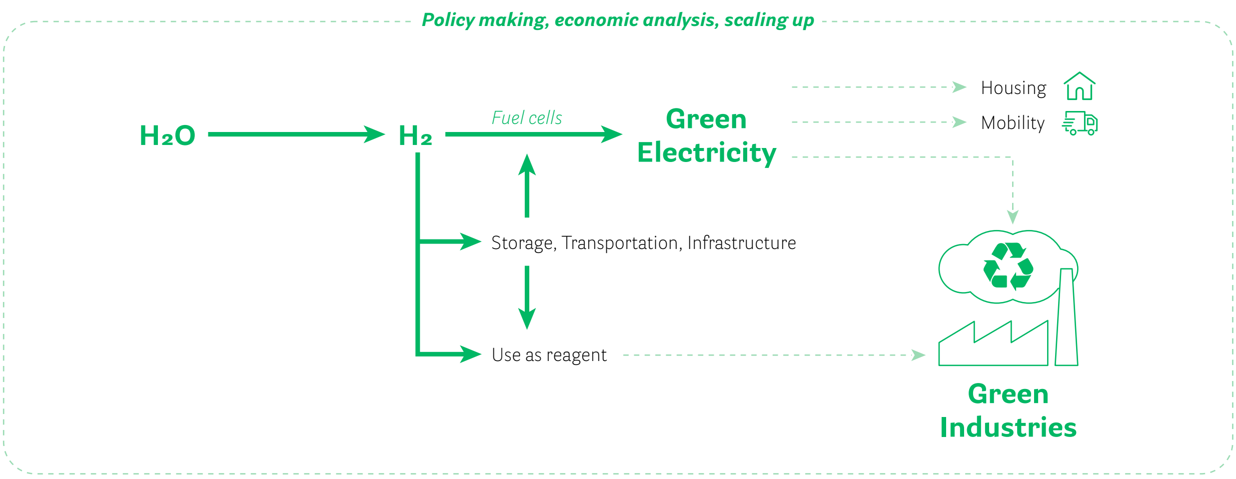
1.2. Hydrogen as Energy Carrier

Hydrogen is a promising energy carrier that can be used in fuel cells to generate electricity, water and heat. Due to the high efficiency and zero- or near zero-emissions operation, hydrogen has the potential to greatly reduce greenhouse gas emissions in many applications. Furthermore, unlike electricity, hydrogen can be stored in large quantities, as well as transported with lower losses than those associated with high-voltage transmission lines.

Historically, the Northern Netherlands region has a strong position in energy production due to the large natural gas fields in the province of Groningen and the energy harbor in the Eemshaven region. In order to decarbonize the energy system, a reduction on natural gas production is taking place, and fossil-based power plants must considerably reduce their carbon footprint. In this context, the development of a green hydrogen economy as a successor to the natural gas economy was initiated, as the region is well suited for such transition. Accordingly, there is potential for producing large amounts of renewable electricity (*i.e.* wind energy), knowledge and physical space to convert it to emission-free hydrogen by electrolysis, coupling opportunities to make good use of the residual heat, an extensive gas infrastructure for hydrogen transportation (also abroad), storage possibilities (*i.e.* in salt caverns) and several industries that could use hydrogen in their processes. Nonetheless, in order to fully realize the green hydrogen economy an integrated approach needs to be employed, as further investments and developments related to the technology, markets, infrastructure, policy and other societal aspects are of paramount importance.

At the University of Groningen, the development of a green hydrogen economy has been evaluated from various perspectives. In the field of hydrogen production through electrolysis, studies are performed to shed a light on the fundamentals of electrochemical reactions and electrocatalysis, and new (bio)catalysts have been investigated aiming for a higher overall efficiency, selectivity and lower costs. [14,15,18,30] In addition to that, the application of thermodynamics and electrochemistry on the design and testing of optimized systems (*i.e.* flexible and efficient fuel cells) helps to bring hydrogen-based technologies (as well as other bioenergy systems, see below) one step closer to realization. [16] The University of Groningen is also one of the partners of the *Hydrohub*, an open testing center (currently under construction at the Zernike Campus in Groningen) where innovations in the field of electrolysis can be translated from the lab to installations of half a megawatt (MW). This research center aims to support the technological development of water electrolysis, as tests on the MW scale will show how the technology will behave when scaled up. When moving from the technical aspects to the implementation of a hydrogen economy, several other challenges need to be addressed. For that reason, our researchers are also involved in economic and legal analyses, environmental policies, market regulations, supply chain and business cases related to green technologies, especially hydrogen. [4,31,32,33,34] Important to mention, the University of Groningen is the academic leader of the *HEAVENN* consortium (see section 4), a large public-private partnership that brings together local municipalities, companies and knowledge organizations aiming to transform the Northern Netherlands into a hub of green hydrogen energy. [33] HEAVENN, an acronym for H_2 Energy Applications (in) Valley Environments (for) Northern Netherlands, is coordinated by the New Energy Coalition network (see section 8) and intends to serve as an international model for energy transition[7]. Accordingly, it will examine how to build on the existing infrastructure of the gas industry to develop large-scale production of green hydrogen, including the retrofit of gas pipelines to transport hydrogen, the development of storage facilities and filling stations, and the incorporation of green hydrogen in a range of uses (such as heating and mobility). Another important consortium in which the University of Groningen participates is the *STORE&GO*, in which 27 European partners investigate the potential of power-to-gas applications (for the production of hydrogen and synthetic natural gas) in the energy grid of three demonstration sites, and our researchers provide environmental, economic, and legal analyses within the project. [4,31,32,35] The hydrogen economy is also addressed in the *PhD@ Sea* NWO program (see section 4) [1,2,4,5], while the *North Sea Energy* TKI program [31] provides opportunities for the integrated implementation of climate-neutral energy systems, *i.e.* large-scale wind energy, hydrogen production and underground carbon storage.

Figure 5. The hydrogen economy in the context of green industries



[7] https://www.newenergycoalition.org/en/hydrogen-valley

1.3. Energy from Biomass

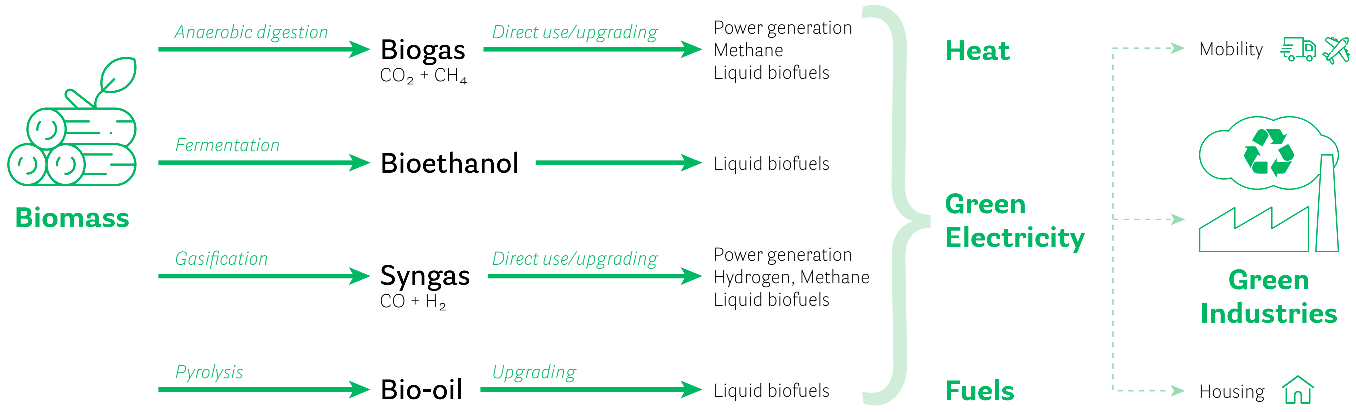
Biomass (organic matter) is the most abundant source of biobased carbon on earth, having great potential as a feedstock for the production of renewable energy in the form of biogas and liquid biofuels. The simple combustion of biomass for heating, a common practice in developing countries, is inefficient and responsible for the release of toxic pollutants. On the other hand, efficiently converting biomass to heat, electricity and energy dense fuels that can be easily transported and integrated in circular value chains represents an important step in the development of green industries.

There are several possible approaches for the obtainment of energy from biomass, and our research groups are active in many of them. For instance, thermochemical routes allow for the production of synthesis gas (via gasification) and bio-oil (via fast pyrolysis) in high yields. The gasification process uses high temperatures and a controlled amount of oxygen and/or steam to convert biomass to synthesis gas (also known as *syngas*), a fuel gas mixture consisting primarily of hydrogen and carbon monoxide. Syngas can be directly used for power generation and serve as an intermediate mixture for the production of synthetic natural gas, hydrogen, methanol and liquid hydrocarbons. Innovative hybrid systems involving biomass gasification, fuel cells and gas turbines are being currently developed, aiming for a sustainable and decentralized energy production from biomass feedstocks. [16] The fast pyrolysis process consists of a rapid heating of biomass in the absence of air, followed by condensation of the vapors into a free flowing liquid mixture (so-called bio-oil). Extensive research has been performed by our groups in this field in order to maximize the bio-oil yield and quality. Besides that, innovative upgrading processes to further convert bio-oil into liquid mixtures with improved properties for fuel applications have been investigated in depth. [36,37,38]

In the field of biochemical routes for biomass conversion, the main routes are anaerobic digestion, in which energy can be obtained in the form of biogas (composed mainly of methane and carbon dioxide), and fermentation for the production of bioethanol and chemicals. These strategies are particularly interesting for processing biowaste, being an efficient alternative technology to combine the production of biofuels with sustainable waste management. [30,39] From a logistics perspective, cost-effective business models for biogas production and transport in the Netherlands are being explored by our researchers within the framework of the *ADAPNER* (adaptive logistics in a circular economy) project. This project examines how the logistic process can be made cheaper and what additional 'green gas' services could be provided, aiming for a lasting boost on the regional economy and to render biogas production cost-effective. [40,41] The obstacles and liability of biogas have been also explored from a legal perspective. [4] The transformation of the main component of biogas (methane) to methanol allows for a liquid fuel that can be readily stored, transported and is amenable to the use in methanol-based fuel cells. In this context, our researchers work on developing novel strategies in catalysis for the transformation of C-H into C-OH bonds using transition metal catalysts. [42]

Another promising strategy for waste management is to use effluent wastewater as a microalgal growth medium. This route has been explored by our researchers using particularly palm oil mill effluent - generated in high amounts in Asia - for microalgae cultivation. A variety of value-added products with fuel applications (such as biodiesel) can be obtained through different cultivation systems, algal species selection and growth strategies. [43] The synthesis of biodiesel through chemical and enzymatic processes involving the (trans)esterification of triglycerides and fatty acids with bio-based alcohols have been also explored [30,36,37]. Furthermore, the University of Groningen is one of the founding fathers of the *Carbohydrate Competence Center* (see section 4), a research center comprising universities and industrial partners that aims to generate, develop and share high-value knowledge in the field of carbohydrates. In line with the aforementioned research topics, one key focus area is the extraction of carbohydrates from biomass and their subsequent conversion to liquid and gaseous biofuels. [30,39]

Figure 6. Routes for energy generation from biomass in the context of green industries



Theme 2

2 Biobased Chemicals & Materials

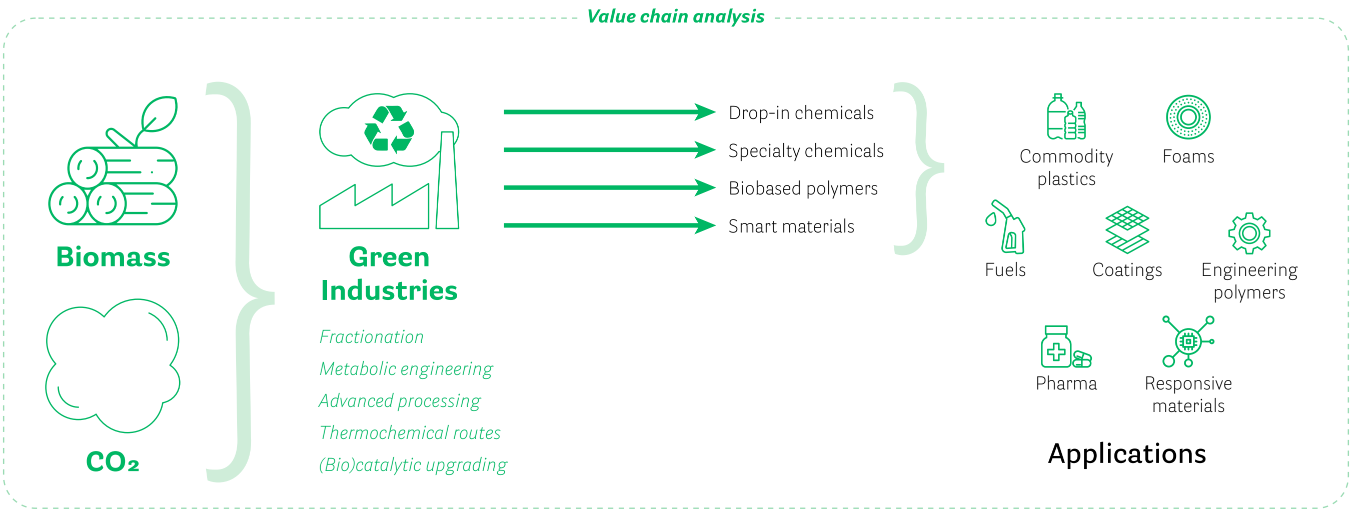
Introduction

In order to supply our society with products and materials in a more sustainable and circular way, decarbonizing the current industrial processes is of paramount importance. With that purpose, studies of new technologies for biomass and CO_2 valorization, as well as the development of greener processing technologies and circular value chains are ongoing at the University of Groningen. Our main ambitions in this field are summarized in Figure 7 and in the bullet points below, and our current efforts in each of the sub-themes (**Strategies for Biomass and CO_2 Valorization**, **Biobased Polymers & Smart materials**, **Catalysis**, **Metabolic Engineering** and **Process Design & Intensification**) will be further detailed in the following sections. Throughout the text, references link specific information to the researcher(s) involved, and a list of contact points is provided in section 5 of this agenda.

Our ambitions

- → *Develop chemical routes to obtain valuable chemicals and materials from biomass and CO_2;*
- → *Design cell factories for a sustainable and cost-effective production of biobased chemicals;*
- → *Develop smart and recyclable materials with a wide range of possible applications;*
- → *Explore green processing technologies using advanced integrated units, milder conditions, biobased (or no) solvents, earth-abundant/metal-free catalysts and biocatalysts;*
- → *Develop novel tailor-made biocatalysts via advanced enzyme-engineering techniques;*
- → *Design possible value chains (operations management, logistics, economics) for novel biobased molecules and materials.*

Figure 7. Biobased chemicals and materials in the context of green industries



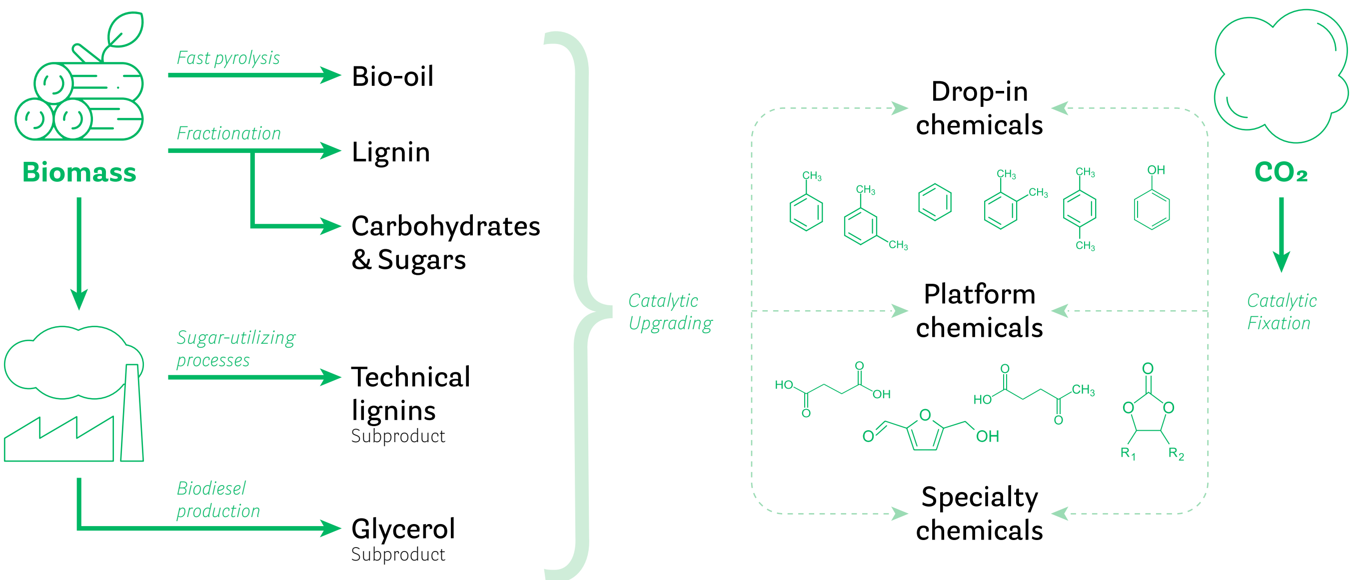
2.1. Strategies for Biomass and CO_2 Valorization

The vast majority of the established industrial processes rely on petroleum and its derivatives for the production of chemicals that are essential in our daily lives. While the industrial sector is undoubtedly a vital source of prosperity and social value on a global scale, its activities also take a toll on the environment, being responsible for a large share of greenhouse gas emissions (28% estimated in 2014). Therefore, new developments are necessary to decarbonize industrial processes, remarkably the use of negative emission technologies for energy production (see sections 1.1, 1.2 and 1.3) and a shift in feedstock from fossil-based to biobased. Such technological shifts must be accompanied by comprehensive value chain analyses able to evaluate all the external factors that come along with the implementation of new techniques, substances, processes and infrastructures (such as operations management, logistics and economics), thus guaranteeing the sustainable delivery of maximum value with the least possible costs. [44]

The field of biomass conversion is full of opportunities and interesting strategies due to the chemically rich structure of this nature-made feedstock. Overall, biomass is composed mainly of carbohydrates (cellulose, starch, hemicellulose) and lignin (an aromatic biopolymer). Depending on the source, these fractions can be processed as a whole or first isolated and processed separately, and upgrading strategies might focus either on innovative biobased molecules or drop-in chemicals, *i.e.* biobased molecules that are identical to their petro-derived peers and can be replaced right away in the current value chains. Our research groups are involved in the investigation of a wide range of processes aiming for the conversion of biomass and biomass fractions into valuable chemicals. For instance, the pyrolysis process has been applied to deconstruct biomass (as well as other highly available feeds such as crude glycerol and plastic waste) into drop-in molecules, particularly BTX (benzene, toluene and xylene). BTX are important building blocks for a myriad of widely used products (*i.e.* plastics, specialty chemicals, solvents, fuels), and its ever growing demand inspired the development of a two-step catalytic pyrolysis process that maximizes BTX yields while allowing for feed flexibility and a robust catalytic step. This technology, so-called Integrated Cascading Catalytic Pyrolysis (ICCP), is being introduced by the start-up *BioBTX*, who strives to become a leader in biobased aromatics and circular economy by transforming biomass feedstocks and plastic waste into BTX (see section 9). [36] Other catalytic and non-catalytic approaches (such as hydrotreatment and oxidation) for the upgrading of bio-oils obtained via pyrolysis to added-value mixtures have been explored in detail by our researchers. [36,38] These approaches are extended to the upgrading of technical lignins, which are overlooked subproducts of biomass-utilizing industries (*i.e.* pulp and paper) with great potential for the obtainment of biobased aromatics and fuel mixtures. While such industrial lignins are degraded and chemically heterogeneous, it is also possible to obtain a highly preserved lignin structure (*i.e.* similar to native lignin) through the mild organosolv fractionation of raw lignocellulosic biomass. This strategy aims to facilitate downstream processing and increase the selectivity towards specialty chemicals while keeping the carbohydrate fraction intact for valorization via specific routes. [38] Moving to the field of carbohydrates, a wide range of processes have also been explored by our research groups, ranging from enzymatic and chemical hydrolysis of carbohydrates into sugar monomers [30,36,37,38,45,46] to further conversion of the sugar monomers into platform chemicals such as 5-hydroxymethylfurfural (HMF). [15,36,37,38,47] HMF is a platform chemical of remarkable importance obtained from the dehydration of hexoses, serving as a precursor for several furan and non-furanic derivatives with a high potential in polymer applications and in food and pharma industries, *e.g.* 2,5-furandicarboxylic acid (FDCA), adipic acid, levulinic acid, caprolactam, diols, etc. Furthermore, our groups investigate the conversion of glycerol (a widely available subproduct from biodiesel production) to among others lactic acid, lactates, methanol and cyclic acetals. [15,36,47] Direct coupling strategies bring several opportunities to novel waste-free, catalytic chemical routes in the development of sustainable industrial processes. Accordingly, a promising strategy recently demonstrated by our researches uses simple alcohols such as ethanol to add alkyl groups to natural amino acids harvested from microbes. The obtained alkylated amines, important building blocks for plastics, pharmaceuticals and more, currently depend on harsh conditions and nonrenewable feedstocks. This novel green approach uses an (earth-abundant) iron catalyst and releases water as its only waste product, having great potential to provide useful starting materials at lower costs both economically and environmentally. [48] Electrochemical routes, which can translate green electricity into chemical bonds, have a notable sustainable character and are the core of the *E2CB* program (see section 4), in which the University of Groningen participates. This program focuses on the development of scalable electrochemical processes to produce fuels and chemicals, and our researchers are particularly active on projects involving electrochemical routes for the conversion of biomass-derived feedstocks into chemical building blocks. [15] The *ARC CBBC* (*Advanced Research Center Chemical Building Blocks Consortium*, see section 4) is a public-private initiative of major importance in the (inter)national context of green industries. This consortium plays a leading role in research towards issues related to circular economy, green chemical processes and clean energy by investigating chemical building blocks for novel sustainable energy and materials. The main priorities of *ARC CBBC* are represented by three research lines (*i.e.* Energy Carriers, Functional Materials and Coatings) located in three research hubs. The hub led by the University of Groningen focuses on the 'Coatings' theme, aiming at a greener approach to both their design and manufacturing. Among the ongoing developments (see sections 2.2 and 2.3 for further details), sustainably sourced building blocks such as chitin, lignin, cellulose and humins are being explored for the development of water-based coatings. [14,18,48,49,50,51,52]

Besides the necessary shift from fossil-based to biobased, carbon capture and utilization (CCU) technologies can help to mitigate global warming by removing CO_2 from the atmosphere and converting it into valuable products. Conceptually, CCU represents a very attractive option in the context of carbon neutrality and circularity. While the high thermodynamic and kinetic stability of CO_2 makes the task challenging, overcoming them is possible by catalytically reacting it with high-energy substrates such as hydrogen, amines or epoxides or by providing an energy input in the form of heat, electric current or radiation. The market for CO_2-based chemicals is considerable, as the possible products include formic acid, methanol and higher alcohols, methane and higher hydrocarbons, cyclic and polymeric carbonates, acrylic acid, urea, among others. Among the routes for CO_2 fixation into valuable chemical products, the 100% atom efficient reaction of CO_2 with epoxides is an attractive valorization pathway for the synthesis of cyclic and polymeric carbonates, being extensively explored by our research groups. [15,53] Furthermore, the reuse of supercritical CO_2 as a green solvent and plasticizer in the synthesis and processing of various polymers is being currently developed and will be detailed in the next section [53]. Another promising route of high industrial relevance comprises the recycling of CO_2 from the flue gas of cement industries, which are responsible for major CO_2 emissions. Accordingly, the *RECODE* project (see section 4) proposes a novel integrated technology platform capable of contributing to a >20% emissions reduction in the medium-long term by reusing the CO_2 for the production of materials (concrete nanofillers) and value-added chemicals (additives for cement formulations). Within the scope of this project, our researchers are particularly involved in the electrochemical conversion of CO_2 into formate. [15] CCS (carbon capture and storage) technologies have been also explored by our researchers, and more information can be found in section 3.3 of this agenda.

Figure 8. Biobased chemicals from the catalytic valorization of biomass streams and CO_2



2.2. Biobased Polymers & Smart Materials

The challenge for carbon neutral and carbon negative technologies involves all industrial processes heavily based on petroleum, naturally including the materials' industry. For instance, major research efforts towards new biobased polymers and overall smart materials are taking place. Biodegradability and recyclability are aspects of great attention and concern in this field due to the vast use of polymeric materials in our daily lives and the waste problem related to them (particularly single use plastics as in packaging and bottles). The development of circular supply chains is thus of paramount importance to achieve a zero waste society, being a regional and national focus[8]. Our researchers are committed to this common goal and work extensively towards waste valorization. Some relevant examples include the conversion of plastic waste into BTX [36], (bio)chemical routes for biowaste conversion into biogas and liquid fuels [30,36], the development of recyclable materials (such as recyclable rubbers and antifouling polymers) [53,54,55] and novel sustainable coatings based on plant waste and crustaceans [48].

Besides sustainable solutions for the widely used commodity plastics (such as PVC, polypropylene, polyethylene), the development of green engineering polymers is very promising due to the possibility of better mechanical and thermal properties, lower costs, lower environmental impacts and easier manufacturing when compared to traditional engineering materials such as wood or metals. Another class of high-performance materials with great potential are smart polymers (also known as functional polymers), which can respond to external stimuli (such as temperature, humidity, pH, chemical compounds, light or an electrical or magnetic field) in various ways, like altering color or transparency, changing shape and becoming conductive or permeable to water. These advanced polymers can be used in a wide range of applications, from highly specialized to everyday products.

Our research groups are involved in the development of various materials from the aforementioned types, prioritizing the use of green solvents and sustainable end-of-life criteria. In the field of biobased polymers, studies are focused on the design, synthesis and characterization of novel tailor-made (biodegradable) macromolecules such as polyurethanes, polyesters, polyamides and polyacrylamides derived from sugars, starches, furans and vegetable oils. Applications include among others coatings, adhesives and resins. [53,55,56] An interesting example is the development of a biobased acrylate resin with application as 'green ink' in stereolithographic 3D printing. [55] Furthermore, by introducing biobased drop-in monomers (such as BTX, see section 2.1) in the current value chains for polymer production, carbon neutral versions of such materials can be readily obtained. [36] Within the *ARC CBBC* consortium (see section 4), the University of Groningen represents one of the three research hubs, and our chemistry experts (together with AkzoNobel, BASF and Nouryon) lead research aiming at the development of novel sustainable coatings. The multilateral current projects approach various aspects regarding the design and manufacture of such materials. For instance, sustainable building blocks based on carbohydrates are being assessed using low-waste photo- or redox-mediated chemical synthesis, with the goal to replace current monomers in coatings formulations. [48] Furthermore, a range of biobased building blocks (*i.e.* chitin, lignin, humins, cellulose) are investigated for the production of sustainable binders to be used in waterborne paints, inks and lacquers. This project also explores novel approaches for obtaining high quality coating films and novel chemical routes for the cross-linking of polymer coatings. [18,48,50] Other related projects will build the necessary fundamental understanding of how parameters like rheology, drying and particle properties govern the movement of the coating components in the paint layer during the drying time, as well as develop waterborne coatings with tunable barrier properties. [48] Polymeric surfactants (also known as amphiphilic polymers) from biobased feedstocks such as algae, sugars and lignin have been also explored by our researchers due to the various potential applications in the fields of biotechnology, nanotechnology, medicine, pharmacology, electronics, etc. The interesting association

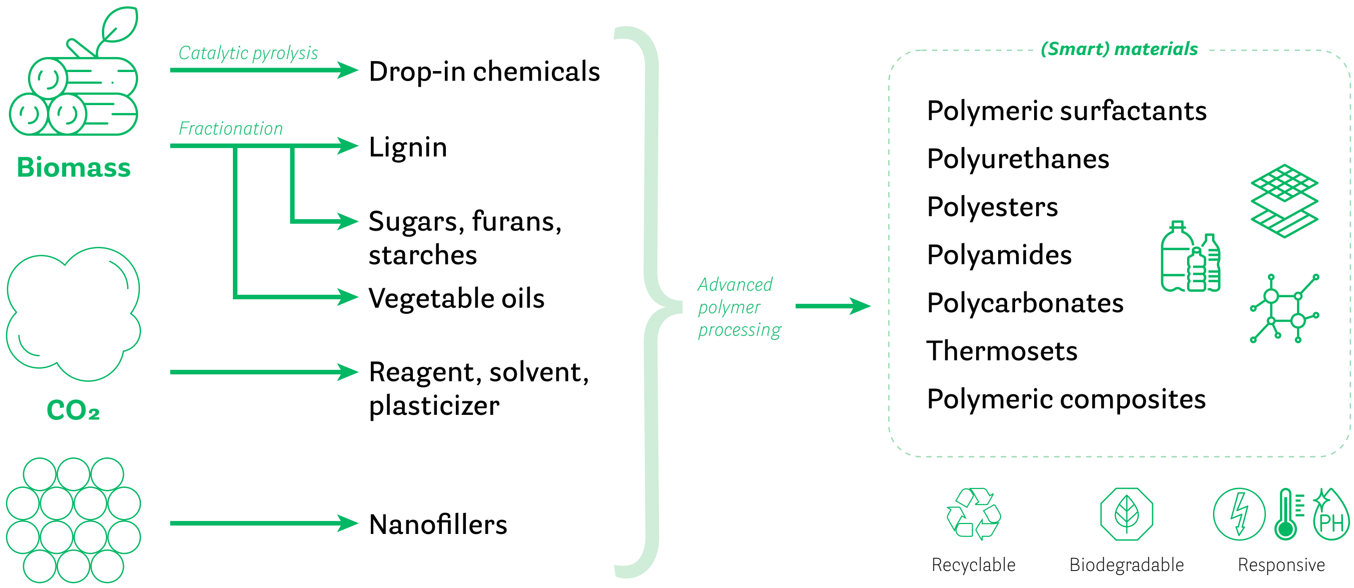
[8] https://www.groningen-seaports.com/industries/circulair/

phenomena of polymeric surfactants in selective solvents results in peculiar rheological behavior and the formation of self-assembled structures. This opens possibilities of introducing responsive behavior to external stimuli, which is at the basis of the design of smart materials. [53,56] The same potential holds for polymeric nanocomposites, in which nanofillers are added to polymers in order to improve the functionalities and add features to the material. For instance, the synergistic effects of each component can result in better mechanical properties, thermal/electrical conductivity and enhanced optical properties. Furthermore, there is the possibility of introducing reversible covalent (via Diels-Alder chemistry) and non-covalent (via hydrogen bonding) interactions which thus confer a reversible nature to the material. Such reversibility is of great interest for the synthesis of materials with self-healing behavior (triggered by light, electricity or heat) and recyclability. Accordingly, a range of thermoreversible materials such as novel fully recyclable rubbers were demonstrated by our researchers. [53,56,57] Antifouling polymeric systems are also under development with the aim to create recyclable coatings able to keep surfaces clean. [54] In the field of characterization, advanced X-ray techniques are being developed to study the nanostructure of materials. Such tools are being used, for instance, to better understand the drying processes of coatings, and hence the correlations between their formulations and final properties. [58]

The field of smart materials based on piezoelectricity, *i.e.* the ability to generate internal electrical charge from applied mechanical stress, is explored by our researchers both from a fundamental and engineering perspective. While the former aims to understand the relationship between structure and functionality of thin film piezoelectric materials, the latter aims to link materials synthesis with devices, which could be made tailored for the specific purpose. The several possible applications of such advanced materials involve energy harvesting for low power and flexible electronics, novel materials for neuromorphic computing (such as memristors), sensors, actuators, etc. Some examples of ongoing projects are: monitoring and energy harvesting from people's footsteps using piezo-tiles; piezoelectric deformable mirrors for aerospace applications; smart actuators for engineering systems. In these projects, our researchers collaborate with municipalities and partner companies. [59,60] Furthermore, various types of ultra-sensitive miniaturized biomimetic sensors (inspired in seal whiskers and cave fishes) have been developed by our researchers. Such affordable, 3D-printed devices have great potential for applications in the healthcare industry - think about personalized health monitoring - and can address key challenges faced in intensive care units such as alleviation of nurses' workload, early diagnosis of injuries and reduction of adverse drug events. [61] Other possible application involves the use of these biomimetic flow sensors in micro-electromechanical systems to create a 3D flow-based image of the surroundings of an aerial vehicle (drone), which is the subject of the *SMART-AGENTS* project (see section 4). [2,61,62,63] Ferroelectric polymers have been also investigated by our researchers, as these materials represent one of the key building blocks for the preparation of flexible electronic devices. For instance, the self-assembly of ferroelectric-based block copolymers, which are highly ordered nanostructures, can be used to prepare functional materials with easily tunable properties. This was demonstrated with the ferroelectric polymer poly(vinylidene fluoride) (PVDF) in a recently developed toolbox, allowing the production of non-toxic and biocompatible materials with tunable properties and vast application potential. [55,58,60]

While the development of (functional) polymers and materials from renewable sources with a biodegradable and/or recyclable character is of paramount importance in the context of green industries, their production methods can have major environmental impacts. For instance, the extensive use of energy and water, as well as organic solvents, catalysts and reagents that are often toxic or dependent on noble metals and fossil resources lead to overall unsustainable and costly processes. Therefore, there is a need to make not only the final product but the production process itself more eco-efficient and competitive. With this purpose, our research groups are involved in the development of greener polymerization routes using novel catalysts and solvent-free approaches. [48,55,57] Furthermore, the use of supercritical CO_2 as a green solvent and plasticizer has received great attention recently due to its inert and non-toxic nature, low cost and simple removal by depressurization. The morphology, cell size and porosity of polymeric products can be controlled by the applied process conditions, opening possibilities for greener production processes of coatings, adhesives, foams, among others. [53]

Figure 9. Advanced polymer processing for the production of biobased and smart materials



2.3. Catalysis

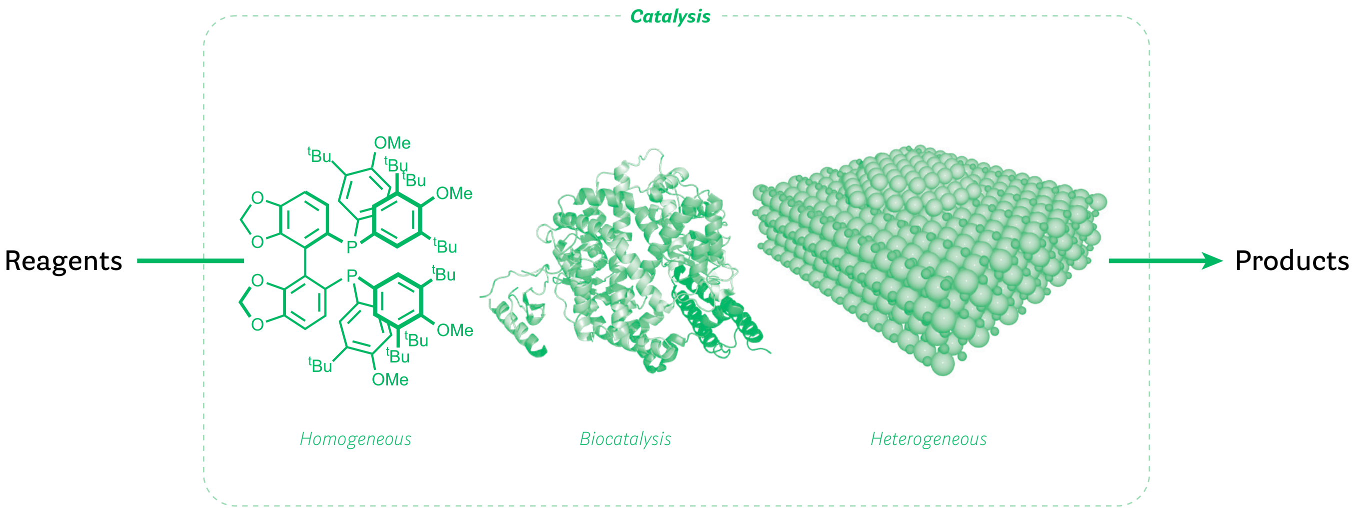
Catalysis plays a major role in the transformations described in the previous sections, being an enabler of high relevance for the development of chemical routes within the green industries. In general lines, catalysts are substances that enable chemical reactions to proceed at a faster rate or under milder conditions than otherwise possible. They are the backbone of industrial processes that use chemical reactions to turn raw materials into useful products, and very often a bottleneck in the development of new processes. For instance, the main difficulties related to the use of catalysts are their costs, availability, stability, recyclability and selectivity towards the desired products.

The broad field of catalysis is remarkably active at the University of Groningen, with contributions from various researchers and different expertise. For the depolymerization of raw biomass and biomass-derived feedstocks (*i.e.* pyrolysis liquids, technical lignins, sugars, glycerol, biogas) into platform chemicals a wide range of heterogeneous catalysts has been investigated, going from the traditional NiMo, CoMo and noble-metal supported catalysts (such as Ru/C and Pd/C) to innovative systems catalyzed by earth-abundant metals (Ni, Cu, Fe), metal-free doped carbon materials, designed zeolites, ores (such as limonite), bimetallic alloys, among others. Homogeneous catalysis with gold and ruthenium-based catalysts, acids and metal salts have also been evaluated, aiming

to find (environmentally friendly) alternatives to access important structural elements in organic chemistry, ideally under mild conditions and absence of additives. [15,17,36,38,42,48] For the conversion of CO_2 into valuable products such as cyclic carbonates, polycarbonates and formic acid, novel homogeneous catalysts based in non-toxic, widely available metals are explored, as well as heterogeneous catalysts such as metal-organic frameworks (MOFs). [15,17] In the field of electrocatalysis and photocatalysis, doped carbon materials, carbon-supported iron complexes and a wide range of homogeneous metal complexes have been explored. [15,18] The well-developed field of asymmetric catalysis has led to unprecedented new chemo- regio- and stereoselective syntheses of biologically active compounds. Furthermore, novel methodologies consisting of low waste catalytic cross coupling with organolithium reagents and renewables' conversion are being explored. [48,49]
In the *ARC CBBC* consortium (see section 4), novel catalysts are being explored for the synthesis of polyesters and curing of coatings. Such catalysts have attractive environmental and economic characteristics (such as low toxicity and high availability) and are expected to lead to more eco-friendly processes, while also broadening the scope of raw materials (including renewable building blocks) that can be used. [14,18,50]
In all catalysis-related studies, a proper catalyst characterization is fundamental to determine structure-activity relations and understand the underlying reaction mechanisms, thus allowing the development of improved catalysts and, ultimately, improved processes. In this context, spectroscopy, which addresses the interaction between matter and electromagnetic radiation, is a powerful tool. Accordingly, through the application of spectroscopic techniques, structural and electronic information under reaction conditions (*in situ*) and during reaction itself (*operando*) can be acquired. Advances on the development of spectroscopic techniques and instrumentation has enabled researchers to take actual 'snapshots' of catalysts and chemical systems, thus getting detailed information at an atomic scale. The field of materials chemistry and spectroscopy (particularly X-ray and Raman spectroscopy) is well-developed at the University of Groningen, and a wide range of homogeneous and heterogeneous catalysts with different functions has been developed and analyzed in detail. [14,18]
A promising technology for the sustainable synthesis of molecules for pharmaceutical, biotechnological and industrial purposes is biocatalysis, which refers to the use of living (biological) systems, such as enzymes, to catalyze chemical reactions. Biocatalysts have many advantages in the context of green chemistry, which include milder reaction conditions (both in terms of pH and temperature), use of environmentally benign solvents (usually water), high catalytic activity and regio-, enantio- and chemo-selectivities for multifunctional molecules and complex feedstocks. Recent advances in biotechnology, particularly protein engineering, have made the production of modified enzymes possible, enabling the development of new non-natural enzymes to obtain novel molecules from a broader substrate range and catalyze transformations that were difficult or nearly impossible using classical synthetic organic chemistry. Furthermore, the growing understanding of sequence–structure relationships is expected to revolutionize the entire field of biocatalysis, opening up the possibility to design tailored enzymes for every given reaction. Our research groups are heavily involved in this field. For instance, natural enzymes are used to modify the structure of starch (by lengthening, shortening and branching its chains) and produce gels and/or liquids depending on the desired application, which can be a sports drink ingredient, bio-friendly adhesive, paper coating, among others. [45] Our vast academic research on the field of carbohydrate-active engineered enzymes has supported the creation of *CarbExplore Research* (see section 9), a consultancy company that offers solutions to the functional food and nutraceutical industry. Novel enzymes are also being explored for the targeted modification of biomass into sugars and sugar-derived functional building blocks [46], and to convert xylan and the lignin fraction of biomass into valuable products.

[38,46,47] Asymmetric (bio)catalysis via the integration of enzymes and transition metal catalysts in multistep/cascade transformations has been investigated in detail for the production of biologically active compounds. [48,64] Further research focuses on redox enzymology to obtain insights in a wide range of biocatalytic transformations, as well as on the enzymes involved in the biodegradation of environmental pollutants. To that end, biocatalytic mechanisms, kinetic properties and structure-function relationships in regio- and enantioselective reactions are studied, leading to the development of new, improved biocatalysts. [47] Such extensive background in enzyme engineering supported the creation of the enzyme-biotech start-up *GECCO* (see section 9), which aims to bridge the gap between fundamental research on enzyme structure and application by providing tailor-made biocatalysts for the production of fine chemicals. Extensive research has been also performed for the discovery and design of novel biocatalysts and biosynthetic pathways for the production of pharmaceutically relevant products and fine chemicals. [64,65,66] Finally, enzymes have been explored as a sustainable replacement of conventional catalysts in radical polymerization processes for the production of biobased and biodegradable polymers. [55]

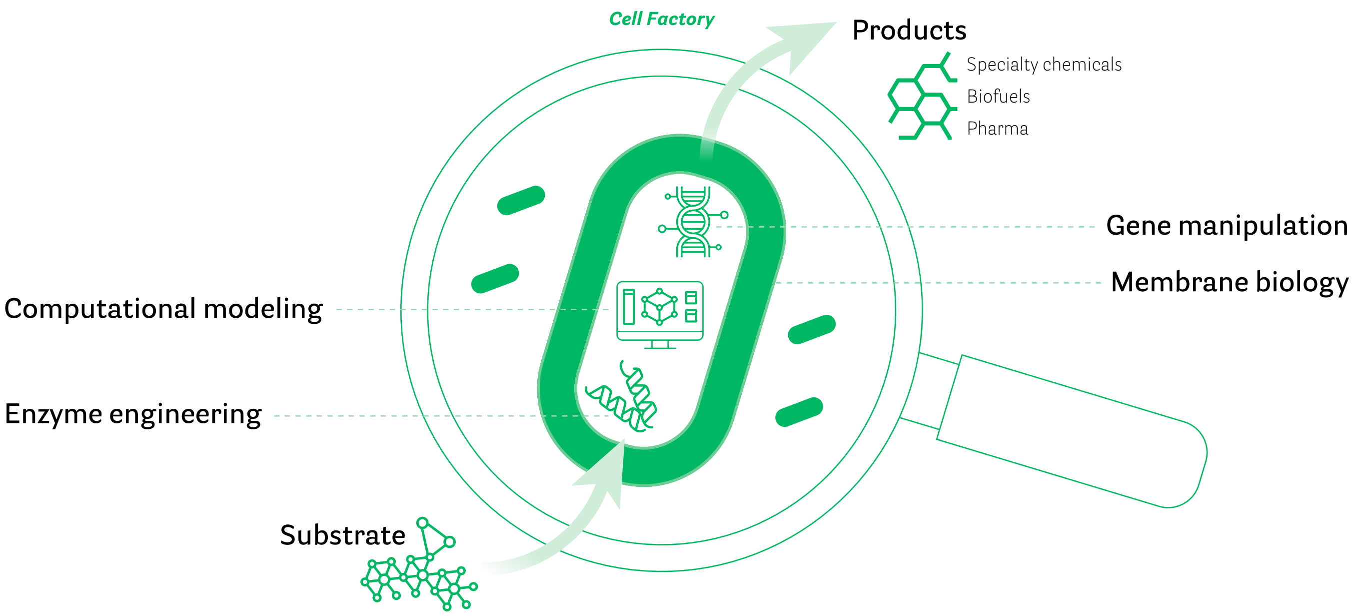
Figure 10. Catalysts are fundamental in the vast majority of chemical processes



2.4. Metabolic Engineering

Microorganisms are bustling with chemistry - for instance, thousands of chemical reactions occur inside cells and microbes to sustain the elemental cycles of carbon, nitrogen, phosphorus and sulfur. Understanding cells' metabolic networks is of paramount importance for the development of biotechnological solutions to address a number of challenges currently faced by society, particularly the sustainable production of valuable chemicals in the so-called cell factories. Metabolic engineering can be defined as the optimization of genetic and regulatory processes within cells to increase the production of a target substance. Research involves the development of mathematical models to understand and identify the bottlenecks of metabolic networks, coupled with the use of advanced genetic engineering techniques (such as protein overexpression or downregulation) to relieve these constraints and achieve high yields of the desired products in a cost-effective way. Accordingly, microbial cell factories hold great potential for the sustainable production of biofuels, pharmaceuticals, nutraceuticals and platform chemicals, being extensively explored by microbiologists, biochemists and biophysicists at the University of Groningen. Our expertise includes among others microbial metabolism, systems biology, single cell analysis and computational modeling [65,67]; membrane biology and protein translocation [68,69]; synthetic biology, enzymology, transport and signal transduction [68]. A remarkable project includes creating a functioning synthetic cell from biomolecular building blocks. Such bottom-up synthesis of a cell is not only a formidable engineering challenge, but will also allow to unravel the principles of biological processes in a truly fundamental way. It is expected that this detailed understanding will simultaneously bring unprecedented opportunities for innovative applications in health, biotechnology, and materials. Another interesting project aimed at engineering the transporter landscape of yeast in order to optimize the co-utilization of pentoses and hexoses from renewable feedstocks for bioethanol production. [65,69] Metabolic engineering can be also applied to boost plant productivity, as shown by the recently funded consortium *GAIN4CROPS* (see section 4), in which highly efficient metabolic pathways will be introduced to increase CO_2 fixation by improving the photorespiration of biomass. [67]

Figure 11. Use of engineered cell factories as biorefineries in the context of green industries



2.5. Process Design & Intensification

When finding a chemical route to obtain biobased fuels, chemicals and materials, proper design and intensification of the process are fundamental for its feasibility. Accordingly, *process intensification* is defined as the targeted improvement of a process at the unit operations in order to increase the efficiency and improve its sustainability' aspects. The microreactor technology is considered a sustainable solution from both safety and energy-saving aspects, as it offers a substantial process intensification due to the enhanced mass and heat transfer rates, as well as the ease of upscaling by numbering-up. The combination of multiple operations in single, highly integrated devices is also in line with the process intensification concept, and one remarkable example is the continuous integrated mixer/separator (CINC) type of reactor. At the University of Groningen, both microreactor and CINC technologies are being applied to the synthesis of valuable biobased chemicals and biodiesel, as well as for the study and optimization of fermentation processes. [30,36,37] It is worth to mention the societal impact that these highly efficient and compact devices potentially have, as they are particularly suited for applications in small scale, mobile units in developing countries. Such impact was nicely demonstrated in a real case study of biodiesel production from rubber seeds in mobile units in Indonesia. [36] The feasibility and supply chain uncertainties (related to production, logistics, socio-economic context, etc.) of this case study were also analyzed in detail by our researchers. [44] Besides efficient reactors, our research groups work with in-line sensors based on the Raman spectroscopy technique to reduce the required energy, materials and risk for personnel, optimizing the process while increasing its safety. [18] Furthermore, the development of smart biosensors and microsensors allows for a successful monitoring and fine control of parameters (such as temperature and pH) in miniaturized biological systems. [30] Overall, the broad range of green processes under development by our groups seek the use of highly integrated and controlled systems, in line with the sustainability and circularity concepts.

3

Theme 3

Systems' Integration & Society

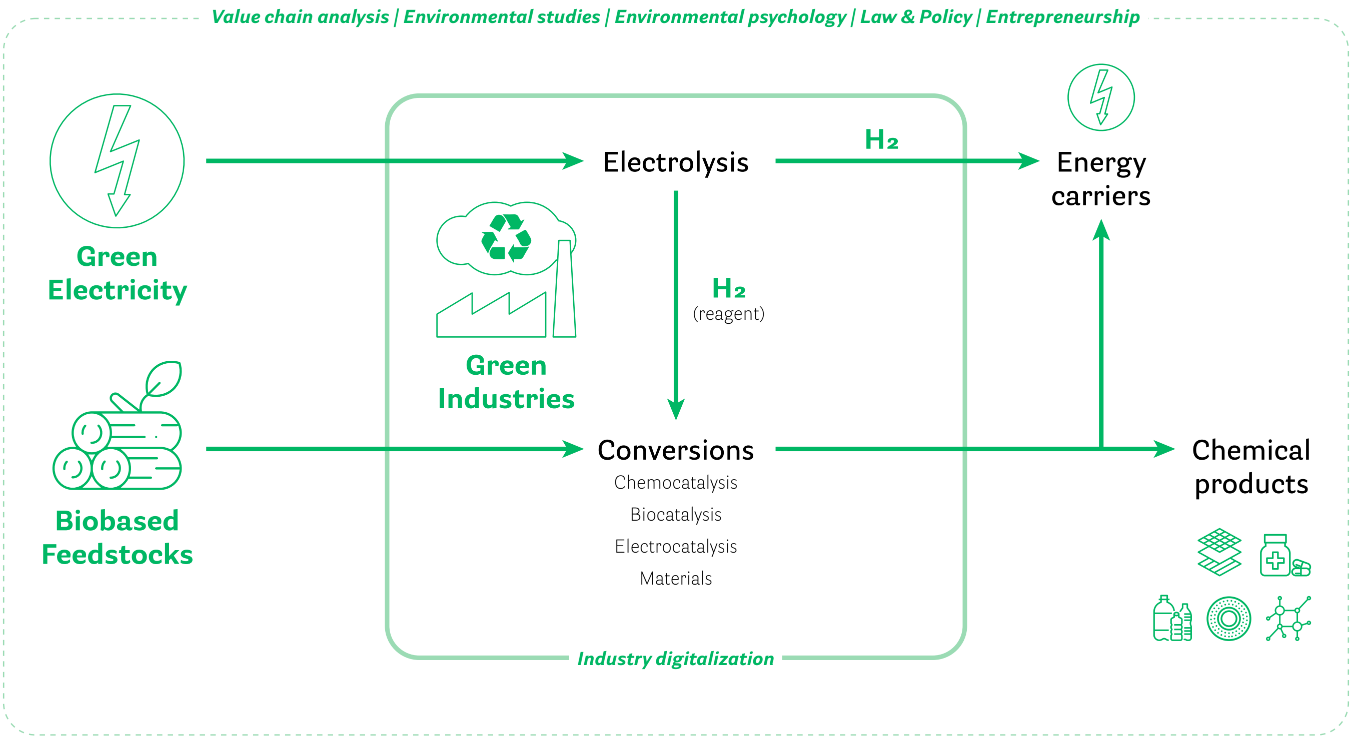
Introduction

The previous sections explored our future perspectives and current research regarding green energy systems and biobased chemicals & smart materials. Most of the described studies are focused on fundamental and technological challenges to obtain new products (chemicals, materials, energy carriers) in line with the sustainability and circularity concepts. Nonetheless, an outer layer of development is essential to make sure that such innovative technologies are feasible, efficient, well regulated and integrated within the society. In this third and last theme, we show the interdisciplinary research carried out at the University of Groningen addressing topics related to Systems' Integration & Society. Based on the previous themes described in this agenda and on the regional potential of Northern Netherlands, Figure 12 shows an example of a well-integrated sustainable chain of green industries. Our main ambitions in this field are summarized in the bullet points below, and our current efforts in each of the sub-themes (**Value Chain Analysis**, **Industry Digitalization**, **Environmental Studies**, **Environmental Psychology**, **Law & Policy** and **Entrepreneurship**) will be further detailed in the following sections. Throughout the text, references link specific information to the researcher(s) involved, and a list of contact points is provided in section 5 of this agenda.

Our ambitions

- *Identify ways to efficiently deliver new sustainable products and services to the market through value chain analysis and industry digitalization;*
- *Evaluate environmental impacts in the context of green industries;*
- *Develop efficient law and policy instruments to regulate and promote green initiatives, particularly in the energy transition process;*
- *Promote the sustainable and social entrepreneurship in a circular economy, new organization models towards a resilient society;*
- *Understand people' perceptions, behaviors and acceptability of sustainable developments, and how to apply this knowledge in policy making as well as in product/service design and implementation.*

Figure 12. A well-integrated chain of green industries



3.1. Value Chain Analysis

A value chain describes the full range of activities needed to transform raw materials/concepts into a higher valued product or service. Companies conduct value chain analyses by evaluating in detail each step of the business with the aim to deliver maximum value for the least possible cost. Closely related are supply chains, which comprises all activities associated with the flow and transformation flows of information, products, materials and funds between the different stages of creating and selling a product, being widely explored to determine where the value chain performance can be further improved. This concept comes from an operational management perspective and stands as an important tool to identify processes that can be reengineered by improvements in connecting, coordinating and controlling activities across linkages. Supply chain research involves various areas (product development, marketing, operations, distribution, finance and customer service), and the so-called green supply chain further integrates an environmental thinking into supply chain management.

The University of Groningen is active in various research fields related to the development of novel (green) value chains, in which all external factors that come along with the implementation of new techniques, substances, processes and infrastructures are evaluated. Researchers from different disciplines often collaborate to deliver complete and well-integrated analyses on topics of major societal importance. For instance, our researchers at the Faculty of Economics and Business investigate decision-making processes related to the production, services and logistic operations within profit as well as nonprofit organizations. Our main research branches include stock management and maintenance planning (*i.e.* estimating the demand for goods and spare parts, monitoring stock levels, managing orders for the purpose of keeping demand and available stock in balance), smart manufacturing and services (*i.e.* Lean, workload management, production planning, information and sensor technologies, robotics), logistics (*i.e.* network design, transport planning, warehouse design) and supply chain management (*i.e.* improving cooperation between partners and coordination/resilience of the various production processes within the value chain). In the context of green industries, operations research involves the supply chain management and integration within (chemical) processing industries (such as food processing) [44], renewable energy development (logistics, systems integration and supply chain, particularly applied to the hydrogen economy) [33], data-driven maintenance planning and optimization [70] and sustainable supply chain (smart manufacturing design, reverse logistics and marketing-operations interface). [71,72]

In the field of economics, quantitative analysis using econometrics models as core methodology are conducted in various areas of finance (such as microeconomics, macroeconomics and industrial organization) [73], and in the field of marketing, three main disciplines are explored, namely strategy, modeling and consumer behavior. [74] Important to mention, the interdisciplinary research cluster *Markets and Sustainability* unites researchers from marketing, operations and microeconomics fields to approach the sustainability question from different perspectives, focusing on how consumers and firms can be influenced to adapt their behavior towards a more sustainable one and how market design and logistic networks can foster sustainability. [32,74]

A remarkable center of applied research within the Faculty of Economics and Business is the *CEER* (*Centre for Energy Economics Research*, see section 8), which focuses on the role of energy in the society through the following core themes: energy-business strategies; consumer behavior and marketing; investments and finance; design of energy markets; macroeconomic relations and environmental policies (such as measures to curb carbon emissions, emission trading schemes, environmental standards and subsidies for renewables). In detail, *CEER* is also actively involved in research regarding the various economic factors that affect the potential of hydrogen as a sustainable solution for heat supply, transport and industrial processes. Current projects on the hydrogen economy address the creation of hydrogen markets, the economic value of the power-to-gas technology as a source of flexibility on energy networks and hydrogen supply from an international perspective. [31,32]

3.2. Industry Digitalization

In essence, industry digitalization (also known as Industry 4.0) is the trend towards automation and data exchange in manufacturing technologies and processes. At the so-called smart industries, cyber-physical systems monitor physical processes, create a virtual copy (*i.e.* a digital twin) of the physical world and facilitate decentralized decision-making. The systems are interconnected, communicating and cooperating with each other and with humans so that every change can be immediately transposed to all other sectors of the value chain. Several digital technologies contribute to the development of smart industries, namely Internet of Things (IoT) platforms, smart sensors, big data analytics and advanced algorithms, customer profiling, etc. In the context of green industries, this translates into predictive maintenance, smart energy consumption, remote monitoring, advanced process control, real-time supply chain and open innovation. The advantages derived from such developments are massive, including a substantial reduction of machinery downtime, lower inventory and maintenance costs, higher forecast accuracy, reduction in time to market and increased productivity and process efficiency.

At the University of Groningen, several topics related to industry digitalization are being investigated by our research groups, ranging from business innovation to data-driven engineering and cyber security. One of them, already mentioned in section 1.1, is the development of smart grids for an optimal alignment of supply and demand of green electricity, which is being tackled from both engineering [2,19,20,21,22,23,24,25,26] and legal [4,29] perspectives. The development of advanced control strategies for mechatronic systems (which are integrated systems comprised of mechanic, electric, electronic and information processing features) and the analysis/control design of nonlinear systems are also paramount for the realization of smart industries. Applications include, among others, chemical processes, biological systems, energy, manufacturing and information technology. The remarkable *DIGITAL TWIN* program, which aims for the development of virtual copies of complex high-tech systems, recently received a large funding from NWO and partner companies (see section 4). [2] Other projects aim for *i*) the achievement of a new generation of high-precision, zero-defect manufacturing processes through the development of advanced control systems and *ii*) a new multi-drone scenario to create a collaborative network that will be demonstrated in two industrial environments (*SMART-AGENTS*, see section 4). [2,61,62,63] In the field of maintenance planning and optimization, large amounts of data are used to improve maintenance decisions through advanced mathematical models. [70] Furthermore, the *DayTime* project involves the University of Groningen and other academic and corporate partners with the objective of using digital twins for predictive maintenance in actual industrial practices. The project will integrate findings and solutions from 14 industrial cases using a generic value chain model. [2] The transformation of industrial production into cyber-physical systems (CPS) is also being studied from a work design perspective, *i.e.* how the (future) capabilities of CPS on the machine, production line, factory and supply chain scope affect job characteristics. [40] Important to mention, our researchers are actively involved in both regional[9] and national[10] *Smart Industry* roadmaps. Further information on industry digitalization topics can be found in the available portfolios *Big Data* and *Digital Society* (see section 10). In addition to that, a dedicated *Academic Roadmap for Smart Industries* was developed by the Industry Relations Office together with key researchers from the field (see section 10).

[9] https://www.nhlstenden.com/nieuws/bedrijfsleven-noord-nederland-wil-met-nhl-stenden-hogeschool-innoveren-smart-industry

[10] https://www.smartindustry.nl/wp-content/uploads/2018/02/Smart-Industry-Roadmap-2018.pdf

3.3. Environmental Studies

Sustainability is a complex global concept that encompasses ecology, economy and social conditions. Therefore, an in-depth, multidisciplinary analysis of the consequences of using natural resources (such as energy, water and soil) along the full chain of activities is essential for the transition towards a more sustainable scenario. At the University of Groningen, models are developed and used to assess various aspects of sustainable development. Examples include the calculation of carbon/sulfur/water footprints, land use along supply chains and environmental impacts related to, among others, urban expansion and dietary changes. [75] Furthermore, the use of complex network theories allows for the analysis of complex energy, environmental and economic systems and how these systems interact. Such advanced models are able to provide an overview of material flows and their environmental (and economic) impacts from either a local, regional or global perspective. [76] Studies of the global carbon cycle based on the occurrence of isotopes are also performed by our research groups. Accordingly, the atmospheric CO_2 greenhouse gas isotopes, together with measurements of CO_2 and O_2 concentrations, make it possible to make an inventory of the natural global carbon-cycle, discriminate between bio- and fossil fuel combustion and ultimately determine the effect of human activities on the cycle. [77] Since CO_2 is a primary greenhouse gas and major concern with respect to climate change, technologies for its fixation and storage have been on the spotlight. While possibilities for CO_2 fixation in chemicals and materials were discussed in the previous sections 2.1 and 2.2, CCS (carbon capture and storage) technologies are addressed by the Geo-Energy research group. The technologies under investigation aim for the subsurface storage of CO_2 emissions (either in pure filtered form or as a flue gas from factories). Other topics include the development of new energy sources in the subsurface such as geothermal energy and heat/cold storage. Overall, our geoscientific research aims to meet the challenges related to a sustainable subsurface exploitation with simultaneous and multiple forms of energy extraction/storage in the context of a densely populated country such as the Netherlands. [78] CCS technologies have been also studied from a legal perspective. For instance, the multi-partner *ALIGN-CCUS* is an important project in this regard, focusing on CO_2 capture, transport, utilization and storage and aiming to accelerate the decarbonization of current industry and power sectors in various European countries. Our law researchers analyze the several related regulatory issues, including the legal framework for re-use of offshore installations and pipelines for the purpose of CCS. [4] Other legal studies within environmental and climate law address instruments, rights and governance for protecting all ecosystem services, stimulating circular economy and waste reduction/ treatment, striving for clean air, water and soil, and combating and mitigating the effects of (as well as adapting to) climate change.

A very important aspect of scientific research is to inform the public and establish a clear connection with society in order to bridge sciences with social contexts. Community and stakeholders must be properly involved in order to understand what must change in science and society when switching to green industries in general (as well as how to tackle the needed measures). The interdisciplinary Science and Society group perform research in the following themes: sustainable land use, food and biotechnology, local energy and animal welfare. In all cases, the key question is how to optimize the development and application of science, taking into account the scientific and societal demands and possibilities. [75,77]

3.4. Environmental Psychology - People's perceptions, behavior and acceptability

While substantial positive impacts are anticipated from the technological developments to decarbonize our value chains, there is a consensus that climate change is also rooted in human behavior patterns. For instance, sustainable solutions will not work as expected if people do not adopt and/or use them properly, and if there is public resistance against such developments. Within this context, the field of environmental psychology plays a fundamental role. Accordingly, this field aims to unravel what drives people' perceptions, behaviors and acceptability of sustainable developments - related to energy use, new sustainable products and technologies, mobility, food - and how to implement this knowledge in policy making and in the design/implementation of products and services.

Various researchers at the University of Groningen are active in understanding environmental behavior, promoting public engagement and designing effective interventions to address climate change mitigation and adaptation, particularly with respect to energy use and mobility. Along with understanding which individual and situational factors affect the intrinsic motivation to act pro-environmentally, studies on which factors affect the effectiveness and acceptability of environmental policy and technologies are carried out. Our researchers work in several interdisciplinary projects that involve, among other topics, the design of socially responsible heat grids; acceptability of a sustainable energy transition; promoting recycling behavior; group identity and bottom-up sustainable initiatives; electric vehicles; smart grids; public participation in the decision-making of sustainable policies and projects (an example is the *RESPECT* project, see section 4). [27,28,79,80,81] Furthermore, in the expertise group Psychometrics and Statistics, the development of advanced statistical models to analyze datasets from social sciences studies supports the understanding of the processes behind human behavior. Among others, such novel statistical models showed that household energy use can be predicted by a mix of sociodemographic, economic and psychological variables. [82]

A remarkable project in the area of humanities and social sciences is *SCOOP* (*Sustainable Cooperation: Roadmaps to a Resilient Society*), which recently received a large funding by the NWO *Gravitation* program (see section 4). This project proposes that cooperation is key to build resilient families, communities, and organizations - but we as a society still don't know how to keep it in the long term, especially in unsettling times marked by major social transformations (think about population aging, mass migration and digital revolution). By integrating the expertise of sociologists, psychologists, historians and philosophers, *SCOOP* investigates novel solutions to enhance sustainable cooperation. An innovative mixed-method research design will assess the effectiveness of such solutions and deliver evidence-based recommendations with concrete benefits for companies and policymakers. [27,83]

3.5. Law & Policy

The University of Groningen always had a special connection with the energy sector, as the region is situated on top of large natural gas fields - for instance, around one third of all the energy produced in the Netherlands comes from the Eemshaven region[11]. The Energy theme is one of the three spearheads of our University, in particular the realization of an energy transition. Such energy transition aims to reduce the use of fossil fuels whilst stimulating energy savings and the use of green energy systems, and legal instruments play a crucial role in this context. Within the Faculty of Law, studies are performed covering the entire energy chain, which includes all legislation and regulation applying to the production, transmission and supply of energy, the promotion of renewable energy sources, the need to secure energy supply as well as issues concerning climate change and environmental protection. Current research is to a large extent focused on liberalization of the energy market in the EU; upstream oil and gas law (*i.e.* licensing, legal changes due to earthquakes following natural gas extraction in the Groningen region, shale gas development in the EU, offshore decommissioning and reuse); legal instruments of climate and environmental law (to protect the ecosystems and stimulate circular economy); legal instruments and the role of access to information, public participation and access to justice in environmental decision-making; new regulatory frameworks for (smart) grids; regulatory challenges in the energy transition (such as the use of renewables, challenges for natural gas production and subsoil use, decommissioning or phasing-out of fossil fuels infrastructures); human rights and (renewable) energy; energy investments in renewable energy sources. In general

[11] https://www.groningen-seaports.com/en/ports/eemshaven/

lines, our research operates on the basis of the physical and economic characteristics of energy systems, analyzing how the law is shaped by such characteristics as well as how the law can impact them. [4,29,34,35,84]

In detail, our researchers are involved in several interdisciplinary projects directly related to the development of green industries. Many of them (such as *SMILE*, *STORE&GO*, *PROMOTioN*, *ALIGN-CCUS*) were mentioned in the previous sections and address the regulatory challenges in the use of power-to-gas technology and electricity storage in the EU [35]; CO_2 capture, transportation and storage from a legal perspective; energy supply security during energy transition; European climate regulation and energy network management; legal frameworks for offshore (smart) grids; governance in the EU energy law with respect to biomass and other renewable sources. [4,29] Market-based instruments to incentivize green electricity and low-carbon industrial output, particularly the efficient design of emissions trading systems, have been extensively explored as well. [34] In the field of environmental and economic law, research tackles current societal themes such as energy transition, industry digitalization and artificial intelligence, aiming to find solutions for dealing with complex market organizations. [29] Overall, the existing technologies, networks, actors and incentives are used to identify the role that law can play to minimize possible hurdles and make the transition towards green technologies easier.

There are natural intersections between law and economy in the development of new policies for green technologies. Ideally, economic growth and environmental sustainability should be complementary, and this can be achieved through a holistic approach in which each aspect is contextualized and studied as part of a whole complex system. Accordingly, market regulations and the overall policymaking related particularly to the energy transition are also approached from an economic perspective by our experts. As aforementioned (see section 3.1), economic studies include, among others, market regulation and competition in gas networks, finance and climate policy, economics of hydrogen markets and carbon credit instruments. [31,32] Finally, policy-related studies on the climate and energy transitions are also performed at the Faculty of Spatial Sciences, as the climate change mitigation and adaptation come with large spatial and societal consequences. Such consequences are investigated with the aim to develop integrated planning strategies for sustainable transformations, particularly energy transition. [5] Further research aims to improve the effectiveness of regulatory tools (widely used by governmental agencies to determine whether a project should be approved and under what conditions) by evaluating in detail the prediction/mitigation/monitoring of impacts, community engagement processes, livelihood restoration, project-induced resettlement and assessment of cumulative impacts. [85]

3.6. Entrepreneurship

Entrepreneurship - the process of designing, launching and running new businesses - is of paramount importance for the development of our society. Great entrepreneurs have the ability to positively change the way we live and work, leading innovations that often improve our living standards, develop communities and promote further research and development, creating wealth, jobs and thus largely contributing to the economy. In the actual context, in which major efforts aim to reconcile economic development and environmental sustainability, entrepreneurship plays a fundamental role on the realization of sustainable solutions in all scales (from local to global), types of business (from technology to services) and areas of expertise.

The University of Groningen has been historically active in the support of entrepreneurs: for example, *Syncom*, nowadays an important player in the pharma and biotechnology industries, was founded in 1988 as a start-up from the university. The entrepreneurial ecosystem in Northern Netherlands has evolved substantially along the years, with the University of Groningen standing as a major partner

in initiatives to provide business support and funding to entrepreneurs (see section 8), as well as a main knowledge center in research involving innovation and entrepreneurship. A detailed list of start-up companies, supported by the University of Groningen and working on the development of green industries, can be found in section 9 of this agenda. For instance, our two entrepreneurship centers (the *University of Groningen Centre of Entrepreneurship* in Zernike Campus and the *Centre for Sustainable Entrepreneurship* in Campus Fryslân, see section 8) aim to solidify our position as an entrepreneurial university through the research, education and support of new business models in line with the sustainability and circularity concepts. The *UGCE* (University of Groningen Centre of Entrepreneurship) is based on three equally important pillars, namely engaged education, excellent research and active business development support. Such a combination of research-based consultancy, academically supported business support and education is a strength of the *UGCE* model. In particular, the *VentureLab North* living lab, which provides support to persons and teams interested in developing growth-oriented, knowledge-intensive enterprises, have helped to launch successful initiatives such as *Ocean Grazer*, *Sustainable Buildings* and *EV Biotech* (see section 9). The research taking place at *UGCE* addresses innovation and entrepreneurship from a network perspective, high-tech/corporate/social entrepreneurship, and qualitative and quantitative support methods and techniques for business development. [86,87]
Sustainable entrepreneurs are key in the transition towards a circular economy, as they generate new products and services that contribute to solving grand societal challenges. Based on that, the *CSE* (*Centre for Sustainable Entrepreneurship*) actively supports the creation of a circular society by providing students, business leaders and academic scholars with the knowledge and competencies necessary to make sustainable entrepreneurship successful. The general framework of sustainable entrepreneurship in a circular economy encompasses the design, implementation and management of sustainable enterprises as well as their social impact on the transition towards a circular economy. [88] The research performed by the University of Groningen in this field is guided by transdisciplinary studies on sustainable business and responsible innovation [89], social entrepreneurship [90], new organizational models for the circular economy [91], cultural heritage [92], environmental behavior [93] and social psychology [94]. Besides offering a wide range of in-depth research projects, policy instruments and best practices including sustainable leadership, organization, collaboration and performance, *CSE* offers the Sustainable Start-up Academy for students, the circular 11-city tour for citizens and science lectures on sustainable entrepreneurship in a circular economy for regional entrepreneurs and policy-makers.
Entrepreneurship is also one of the research themes within the Faculty of Spatial Sciences. For instance, a key feature of entrepreneurship is its local nature, and this leads to large geographical differences in the intensity, characteristics and impact of entrepreneurial activities. Studies on the spatially different features of entrepreneurship are performed by our researchers in order to better understand the regional disparities in socioeconomic development and well-being. [95] Further research in the field of purposeful entrepreneurship focuses on the development of sustainable, circular, sharing and social initiatives, sustainable employment and the enhancement of regional entrepreneurial ecosystems. Such multidisciplinary studies aim to generate results directly applicable to the Northern Netherlands region, for example by adjusting regional policy (government level) and providing recommendations and practical tools to local companies and small businesses. [96]

4 Examples of Current Research Projects

The University of Groningen participates in a wide range of consortia, partnering with important academic institutions, governmental entities and companies with the common goal to develop systems, materials and chemicals in line with the sustainability and circularity concepts, as well as resilient societies based on sustainable cooperation. We showcase below some remarkable ongoing initiatives in the context of green industries, which together acquired more than €100 million in terms of project budget (both from public and private sectors).

Advanced Research Center Chemical Building Blocks Consortium (ARC CBBC) [48]

The ARC CBBC is the Dutch national research center that investigates chemical building blocks for novel sustainable energy and materials. This joined academic-industrial-governmental partnership involves three hub universities (University of Groningen, Utrecht University and Eindhoven University of Technology), major chemical companies in the Netherlands (Shell, AkzoNobel, BASF, Nouryon), NWO, Holland Chemistry and the Netherlands Ministry of Economic Affairs and Climate Policy. The ARC CBBC initiative is running a 10-year program (> €10 million/year) on three main themes, namely Energy carriers, Functional materials & specialties and Coatings, aiming at building the future sustainable chemical industry in the Netherlands. One of the three 'hub locations' is the University of Groningen (focused on the Coatings theme), in which investments of more than €1.5 million/year support various research projects on sustainable materials/coatings and catalysis. **More information here.**

Carbohydrate Competence Center (CCC) [30,39]

The CCC was established by the University of Groningen and Wageningen University & Research to generate and develop high-quality knowledge in the field of carbohydrates, with the aim of stimulating innovation and contributing to a healthier and more sustainable society. CCC research is demand-driven, fundamental and in the precompetitive phase, with the participation of important industrial partners such as DSM, FrieslandCampina, Avebe and Royal Cosun. The CCC management develops private-public partnerships (PPP's) in which industries work together with knowledge institutes. Since its start in 2008, several research programs have already been completed, representing a budget of €34 million. Currently, three research programs are under implementation, with a total budget of €10 million, half of which is financed by industries. Two of these research programs are part of the NWO-CCC partnership (50% subsidy from NWO). **More information here.**

Co-Fluid Catalytic Cracking of Pyrolysis Liquids in Existing Refineries (CoRe) [36]

Among the technologies for converting biomass into higher-quality products, pyrolysis is one of the most interesting. The pyrolysis technique has developed strongly in recent years and the Netherlands is market leader, with among others companies such as BTG (Biomass Technology Group BV). This technology is applicable for a wide range of biomass, and suitable for low-value biomass as well as agricultural residues. However, the primary product (pyrolysis oil) is not directly applicable as a transportation fuel and must first undergo further treatment for commercial applications. The CoRe project will focus on valorizing pyrolysis liquids in existing refineries by co-feeding them in typical refinery FCC feeds to obtain green fuels and bulk chemicals. For this project, Prof. Erik Heeres (Faculty of Science and Engineering, University of Groningen) received a project budget of €500.000 (Topsector Bio-Based Economy grant from the ministry of Economic affairs). **More information here.**

Electrons to Chemical Bonds (E2CB) [15]

Each year, NWO awards Perspectief funding to new research programs in areas in which Dutch industry and research centers are strengthening their position. The six research programs selected in 2018, among those the Electrons to Chemical Bonds (E2CB), have a joint project budget of €28 million. E2CB will tackle the decarbonization on the Dutch chemical industry by using electrochemical strategies, which can both reduce CO_2 emissions and make it possible to store excess supplies of green electricity in chemical bonds. Currently, few electrochemical processes are known that can be used on an industrial scale, and the consortium will focus on the entire chain: from materials research at the nanoscale up to different types of reactors at the macro scale. The researchers aim to develop new scalable electrochemical processes to produce among others methane, liquid hydrocarbons and ammonia, as well as to convert biomass into useful chemical building blocks. Prof. Paolo Pescarmona (Faculty of Science and Engineering, University of Groningen) is involved particularly on the latter research branch (electrochemical conversion of biomass). **More information here.**

Facilitating Large Scale Offshore Wind Production by Developing Offshore Storage and Transport Alternatives (PhD@Sea program) [4]

The Boards of the NWO domains Science and Social Science and Humanities have approved a project proposal worth €1.1 million coordinated by Prof. Martha Roggenkamp (Faculty of Law, University of Groningen) within the PhD@Sea program. The project analyzes the feasibility of bringing large amounts of offshore wind energy to shore, varying from offshore energy storage and hydrogen conversion to novel methods to transport electricity and/or hydrogen. The planned research is highly interdisciplinary and will be based on novel technologies, focusing on the assessment of their feasibility and technical challenges whilst also taking into account explicit market, legal/regulatory frameworks and spatial planning considerations. **More information here.**

GAIN4CROPS [67]

The GAIN4CROPS consortium aims to boost plant productivity using novel strategies to minimize the inefficiencies of photorespiration. Photorespiration reduces CO_2 assimilation efficiency (and thus biomass yield) by ~30%, representing a prime target for improving agricultural productivity. GAIN4CROPS will follow a stepwise approach, starting by engineering naturally occurring carbon pumps and culminating with the introduction of highly efficient synthetic metabolic pathways that can dramatically boost carbon fixation. It will serve as a research and innovation roadmap to attain similarly higher photosynthetic performance in a broad range of C3 crops. In total, the consortium received a project budget of €8 million, being €500.000 destined for research on energy dissipation to be performed by Prof. Matthias Heinemann (Faculty of Science and Engineering, University of Groningen).
More information here.

Green Process Technology with Supercritical CO_2 [53]

Production processes must become greener and lead to fewer CO_2 emissions, and supercritical CO_2 can play an important role in this by acting as a green solvent. SMEs may soon be able to profit from innovative applications of this green solvent and, as a result, reduce their waste, emissions from damaging substances and energy use. But how can small companies deploy supercritical CO_2 for the environmentally-friendly production of sustainable chemical products? This question is central to the four-year project being conducted by Prof. Francesco Picchioni (Faculty of Science and Engineering, University of Groningen) and partners from the Hanze University of Applied Sciences and seven companies. The Province of Groningen and the Northern Netherlands Alliance (SNN) are jointly supporting the initiative with a project budget of around €3.8 million. **More information here.**

Hydrohub Megawatt Test Centre [15, 36]

This project covers the design, realization and exploration of the Hydrohub Megawatt Test Centre at the Zernike Campus in Groningen. The open-innovation infrastructure will be used to do research and perform series of testing at MW scale with water electrolysis, serving as a stepping stone towards future Gigawatt scale industrial production of sustainable hydrogen. The technological developments at the Hydrohub MW Test Centre should lead to a cost price for the electrolysis column of €50-100/kW with an efficiency of over 80% (for the first five years of use) and a pressure of 30 bar by 2030. ISPT is the initiator of the project, together with EnTranCe, University of Groningen, Nouryon, Yara, Gasunie, Shell, Frames, Groningen Seaports, Yokogawa, TNO and the Province of Groningen. A total project budget of €6.9 million was designated for the construction of the Hydrohub, which is expected to be operational by 2020. **More information** here.

Hydrogen Energy Applications for Valley Environments in Northern Netherlands (HEAVENN) [33]

The HEAVENN project is intended to serve as a blueprint for energy transition internationally. It will examine how to build on the existing infrastructure of the gas industry to develop large-scale production of green hydrogen, an energy resource produced from renewable sources. The project has been selected by the European Commission with a total (public and private) project budget of €90 million. HEAVENN brings together the core elements of a hydrogen economy: production, distribution, storage and local end-use of hydrogen into a fully-integrated and functioning "H_2 valley" (H2V), that can serve as a blueprint for replication across Europe and beyond. Projects that will be supported by the grant involve the large-scale production of green hydrogen as a feedstock for industry, storage, transportation and distribution of hydrogen and hydrogen applications in industry, the built environment and the mobility sector. The associate professor Evrim Ursavas (Faculty of Economics and Business, University of Groningen) is the academic lead of this project. **More information** here.

Integration of Data-driven and Model-based Engineering in Future Industrial Technology with Value Chain Optimization (DIGITAL TWIN) [2]

High-tech systems are becoming increasingly complex and difficult to design, produce and maintain. The DIGITAL TWIN program develops methods to make accurate digital twins of such systems: virtual software versions, which allow you to run predictive simulations. These simulations can predict, for example, how changes in the design will influence performance or which part is due for maintenance at what time. The DIGITAL TWIN program has received a €4 million project budget from the Perspective program of the Dutch Research Council (NWO), and the participating companies have added another €1.6 million to that figure. There are researchers from six universities working on the program, among them Prof. Bayu Jayawardhana (Faculty of Science and Engineering, University of Groningen). They are working together with 12 industrial partners from the high-tech, metal and composites industries, including ASML, VDL Groep, Tata Steel, Philips and Océ. **More information** here.

Next Generation Organic Photovoltaics [8]

The Focus Group Next generation organic photovoltaics, awarded with a €5.2 million project budget from NWO, works on enabling and realizing the next generation of Organic Photovoltaics (OPV) through the development of OPV science. The research program managed by Prof. Kees Hummelen (Faculty of Science and Engineering, University of Groningen) is based on a multidisciplinary approach where physics, photophysics, device physics, organic chemistry, material science, and theoretical modeling are combined synergistically. The goal is to enable PV technologies within the next 10 years that will lead to mass production within the accepted roadmap for solar technology. **More information** here.

Recycling Carbon Dioxide in the Cement Industry to Produce Added-value Additives: A Step towards a CO_2 Circular Economy (RECODE) [15]

In the RECODE project, awarded with a €7.9 million project budget from the EU (Horizon 2020), CO_2 from the flue gases of a rotary kiln in a cement industry will be used for the production of value-added chemicals (additives for cement formulations) and materials ($CaCO_3$ nanoparticles to be used as concrete fillers). A circular-economy-approach is enabled, as the CO_2 produced by cement manufacturing is reused within the plant itself to produce better cement-related products leading to lower energy use and CO_2 emissions. Distinctive features of the RECODE approach are the high process intensification and scale-up-ability; the use of low-grade heat sources; the meaningful reduction of CO_2 emissions (>20% accounting for direct and indirect means) and the good market potential of their products at a mass production scale. Within the project scope, Prof. Paolo Pescarmona (Faculty of Science and Engineering, University of Groningen) is involved on the electrochemical conversion of CO_2 to value-added chemicals. **More information** **here.**

Renewable Energy Strategies: Effective Public Engagement in Climate Policy and Energy Transition (RESPECT) [80]

Renewable energy projects often face public resistance, especially if people feel excluded from the decision-making. Public participation early in the decision-making process could lead to more socially acceptable energy projects. However, public participation is currently focused on local energy projects, while important decisions are made at macro level in policy visions, plans, and programs. This may reduce public influence and fuel public resistance. One solution is to include public participation in macro-level decision-making. Yet, little is known about how this can be done and how this would affect the acceptability of energy projects. This project, led by the associate professor Goda Perlaviciute (Faculty of Behavioural and Social Sciences, University of Groningen), has recently received a project budget of €500.000 from the NWO program MARET (Societal aspects of the regional energy transition), and will develop a novel, interdisciplinary approach on how to optimize public participation at all levels of decision-making to reach more socially acceptable decisions. **More information** **here.**

Soft Advances Materials [55]

The NWO Science Domain Board has awarded a project budget of €3.6 million to this consortium of four companies and eight knowledge institutions active in materials research. The multidisciplinary consortium led by Prof. Katja Loos (Faculty of Science and Engineering, University of Groningen) will develop new and improved sustainable materials. The companies will jointly contribute with €1 million to this project within the Top Sector Chemistry. In detail, the research goal is to design materials and control their structure from the atomic and nanometer scale up to macroscopic dimensions. Whether this control is achieved through sophisticated (macro)molecular synthesis, deposition, or advanced processing, understanding the interactions among these dimensions is key. Theories and computational methods will be combined with advanced synthesis and characterization techniques to control matter and understand its behavior over the essential length scales. **More information** **here.**

Sustainable Cooperation: Roadmaps to a Resilient Society (SCOOP) [83]

The SCOOP project is dedicated to the interdisciplinary study of sustainable cooperation as a key feature of resilient societies, connecting research groups from sociology, psychology, history, philosophy, public administration, research methods, and statistics. The program is under the leadership of Prof. Rafael Wittek (Faculty of Behavioural and Social Sciences, University of Groningen) and involves researchers from Utrecht University, VU Amsterdam, the Erasmus University Rotterdam and Radboud University Nijmegen. The project was awarded a project budget of €18.8 million from the NWO program

Gravitation. SCOOP ties in with the route 'Resilient and meaningful societies' from the Dutch National Research Agenda. **More information here.**

Swarm Collaborative Multi-agent Cyber Physical Systems with Shared Sensing Modalities, 5G Communication and Micro-electromechanical Sensor Arrays (SMART-AGENTS) [62]

The SMART-AGENTS project, funded by the NWO Smart Industry 2019 program, proposes a new multi-drone scenario to create a collaborative network. The system will be demonstrated in two industrial environments (logistics and agriculture) for counting inventory in a warehouse and monitoring plants in greenhouses, respectively. In this project, researchers from both engineering and computer science disciplines (Dr. Ajay Kottapalli, Prof. Bayu Jayawardhana, Dr. Kerstin Bunte and Dr. Michael Wilkinson from the Faculty of Science and Engineering, University of Groningen) will collaborate to build up this network and test it with industrial partners. **More information here.**

Top-down Energy Projects as Catalysts for Bottom-up Local Energy Initiatives (TOP-UP) [27]

Within the ERA-Net Regional Energy Systems (RegSys) call, three proposals have been selected for a NWO project budget of about €2.1 million. One of the awarded projects is the TOP-UP, led by Prof. Linda Steg (Faculty of Behavioural and Social Sciences, University of Groningen). This project will examine how heat networks can be better integrated into electricity networks, for example, by identifying how surpluses in one net could be used in another. Opportunities exist for local actors (consumers) and business sectors (e.g. agriculture, industry) to participate more actively in the energy system, for instance by making their own energy storage equipment systems available, or by selling the energy they themselves generate. In this way, 'top-down' interventions such as the construction of a heat transport network could lead to more 'bottom-up' participation. The studies will be carried out in Groningen, Copenhagen and elsewhere, and the participating organizations and companies are the University of Groningen, the Technical University of Denmark, Enpuls, Enexis, Powerchainger, Høje-Taastrup district heating, and the municipalities of Groningen and Høje-Taastrup. **More information here.**

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6 Scholarly Output & Current Collaborations

The University of Groningen is a European leader in terms of academic research, numbering in the world's Top 100 according to various acclaimed international rankings[12]. This success is a result of high-quality research taking place at our institutes, which aim to understand and solve major societal problems related to health and well-being, sustainability, technology, among others. Groningen-based researchers collaborate with colleagues from all over the world, while actively involving students in their projects.

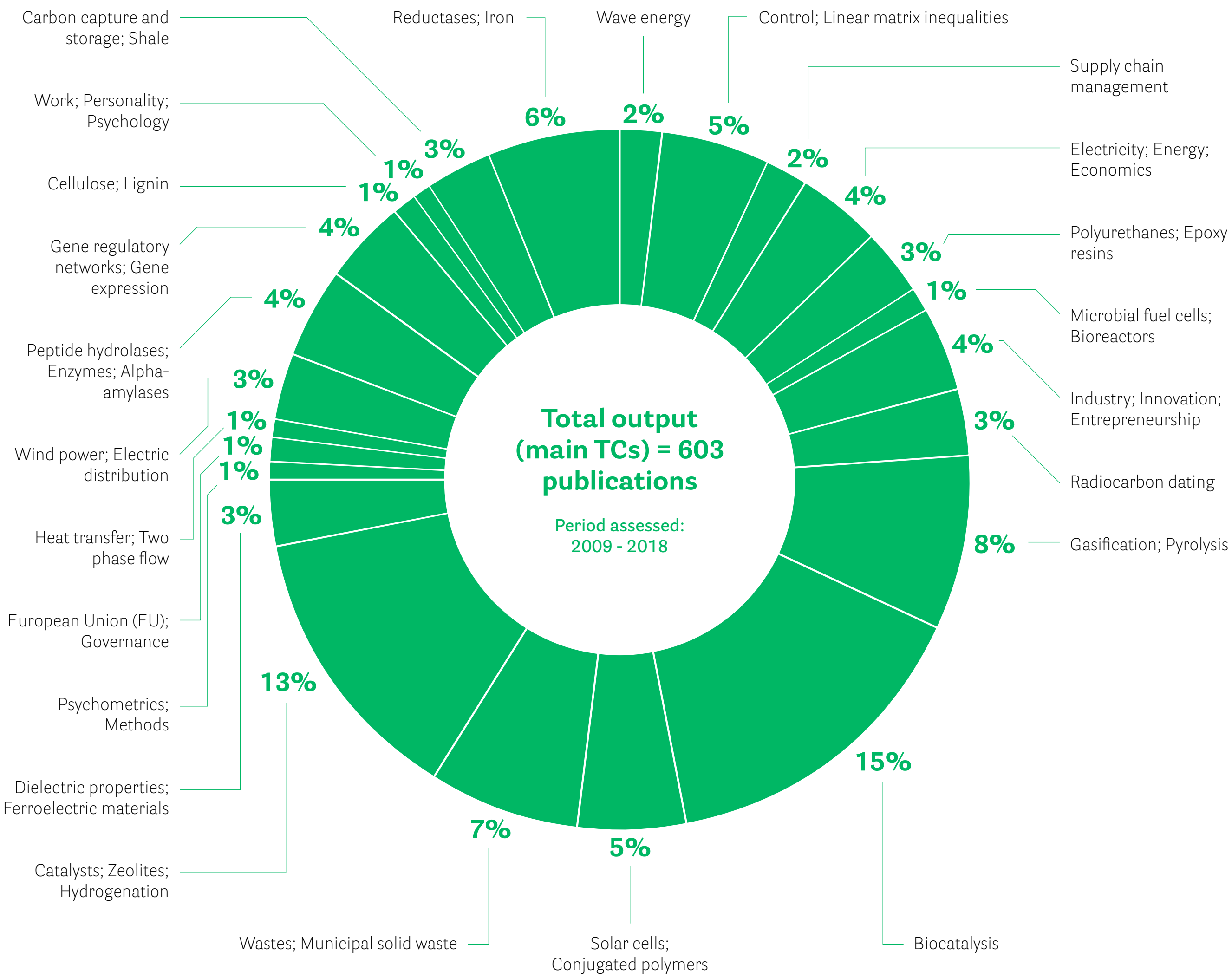
To give an idea of our research output and current collaborations in the context of green industries, research analytics were initially used to map the work of 28 representative researchers selected from all seven faculties participating in this innovation agenda. This assessment was possible thanks to the support of the Research Impact Services[13] from the University of Groningen Library. Scival[14], a bibliometric platform powered by the Elsevier Scopus database of peer-reviewed literature, was used to obtain insights related to research performance, trends and collaborative partnerships. In the analyzed period of 2009-2018, an impressive scholarly output of 1525 publications was observed for the group of representative researchers, averaging 6 publications per researcher per year. By selecting the main topic cluster of each researcher, around 40% of this output could be further categorized. The distribution of scholarly output per topic cluster is depicted in Figure 13, showing the interdisciplinary and complimentary character of the research performed at the University of Groningen. Important to mention, more than 50% of this output involve collaborations with academic and non-academic partners, among those well-known universities, research centers and companies from the Netherlands and abroad.

[12] https://www.rug.nl/about-ug/profile/facts-and-figures/position-international-rankings

[13] https://www.rug.nl/library/research-impact-services

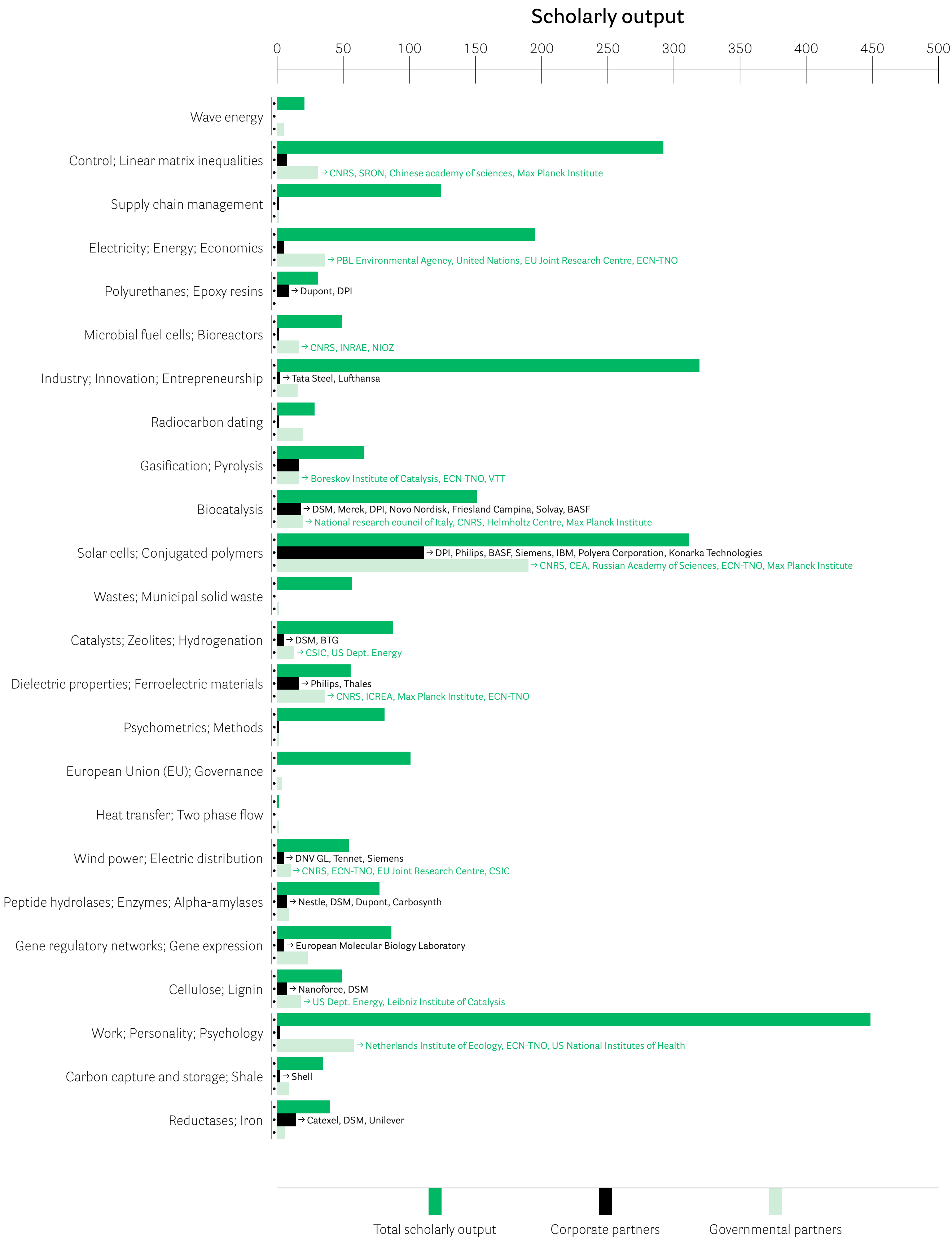
[14] https://www.scival.com

Figure 13. Scholarly output distribution of the examples of topic clusters (TCs) related to green industry research, based on a representative group of researchers from the University of Groningen



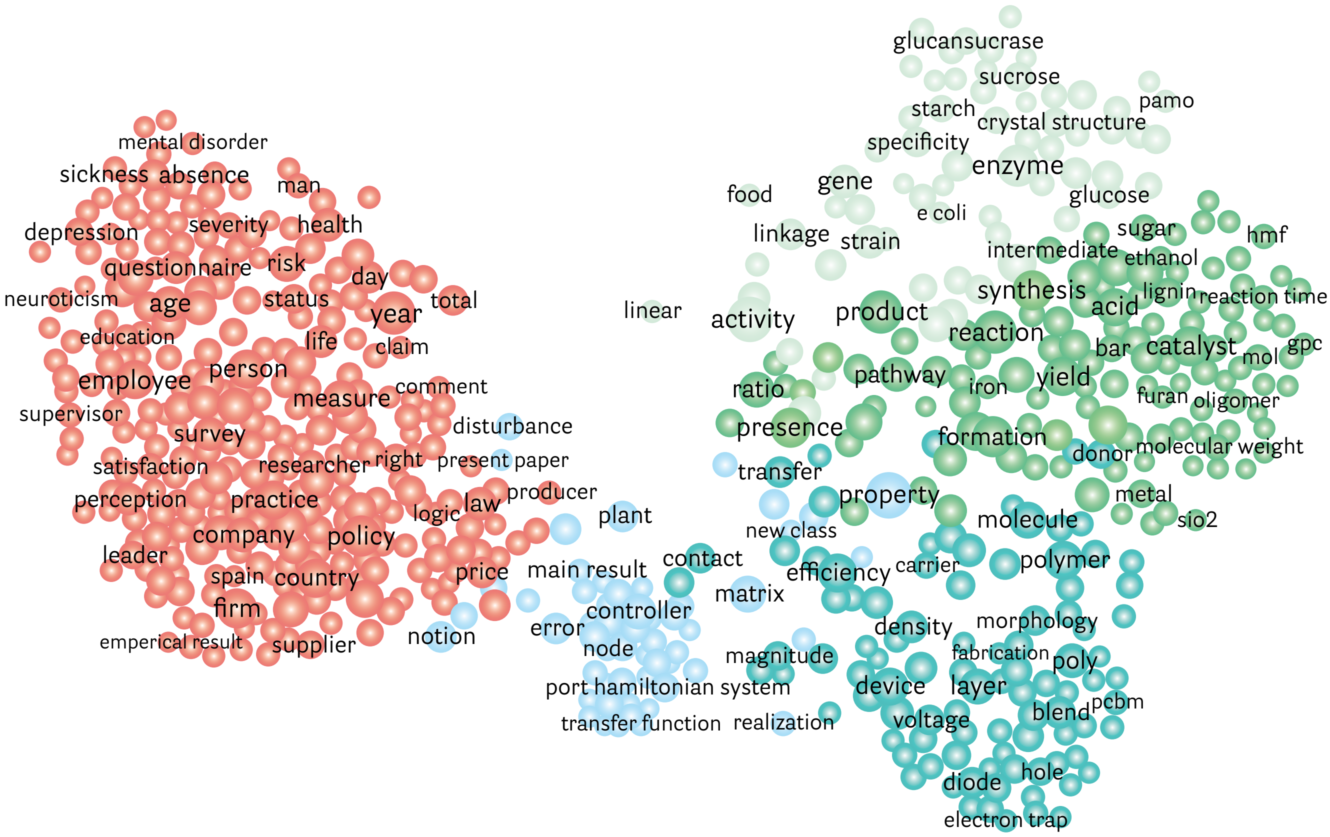
We further extended the analysis to all the research performed by the University of Groningen in the selected topic clusters in the same period of 2009-2018, aiming to obtain a complete overview of our performance and collaborations beyond the selected group of researchers initially evaluated. This analysis resulted in an impressive sum of 2775 publications (with more than 70000 citations) involving 1994 authors from several universities around the world, as well as substantial national and international partnerships with governmental research centers (around 20% of the publications involve among others *ECN-TNO*, *CNRS*, *Max Planck Institute* and the *United Nations*) and industries (around 10% of the publications involve among others *DSM*, *DuPont*, *BASF*, *Philips*, *Shell* and *Siemens*), see Figure 14.

Figure 14. Global scholarly output of the University of Groningen per main topic cluster in the period of 2009 - 2018, including examples of collaborations with corporate and government partners



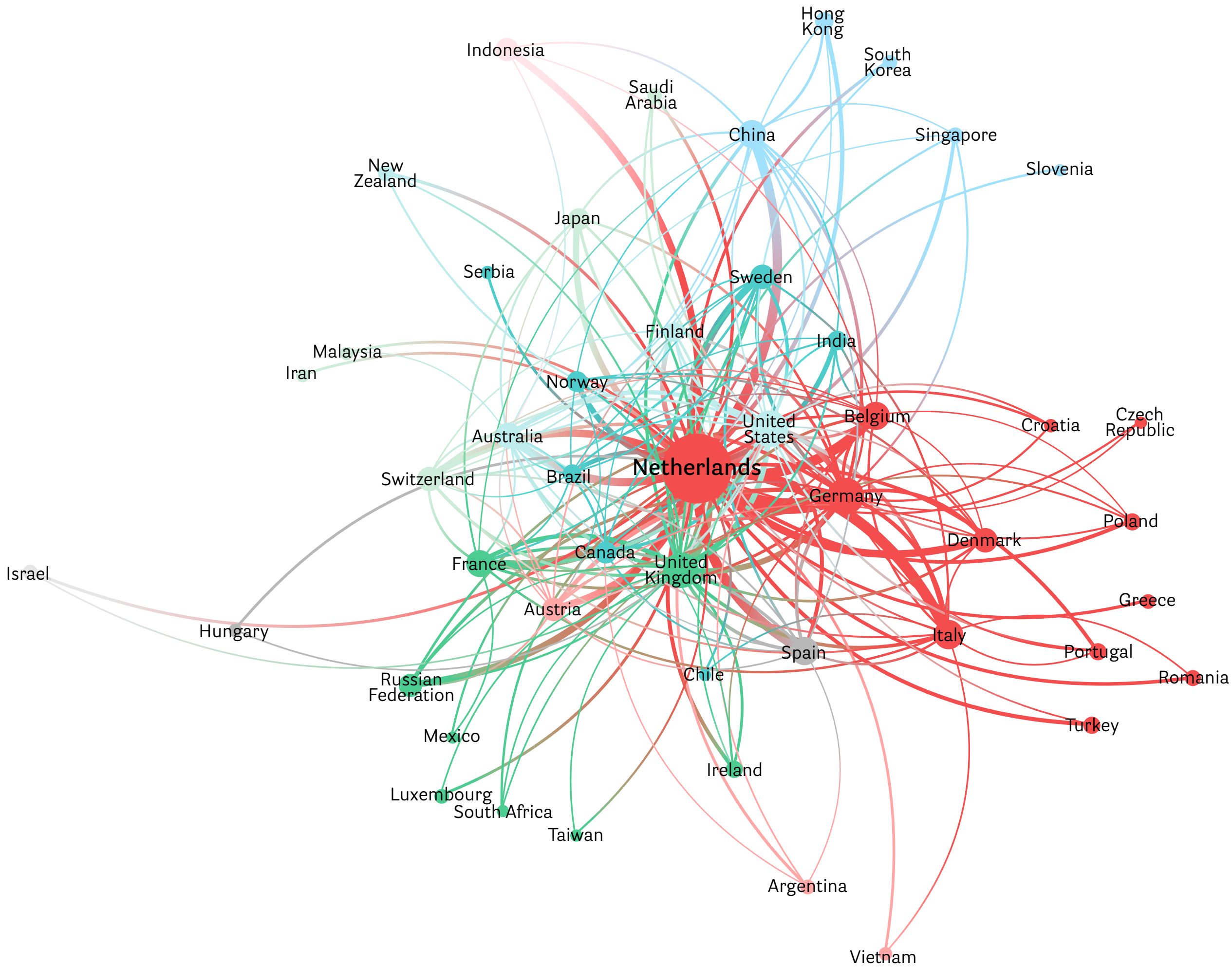
Finally, a visualization of the bibliometric network was obtained through textual data mining applied to the selected scientific literature, showing how interconnected and diverse the main terms from the selected topic clusters are (Figure 15). Furthermore, the country co-authorship map (Figure 16) shows our main collaborations in the selected topic clusters, which include various EU (such as France, Germany and Italy) and non-EU countries (such as Australia, China and Indonesia). Accordingly, the University of Groningen is a strong academic player from both a regional/national and global perspective, actively contributing to the development of sustainable solutions together with (inter) national partners. With this overview, we aim to show the collaborative and interdisciplinary profile of the University of Groningen within the topics directly related to the development of green industries.

Figure 15. Term map based on the scholarly output of the selected topic clusters. Node size: term occurrence; node proximity: term relatedness; node color: topic cluster. Generated by VOSviewer[15]



[15] https://www.vosviewer.com

Figure 16. Country co-authorship map based on the scholarly output of the selected topic clusters (countries with >5 co-authored publications). Node: country; node size: number of documents; node proximity: relatedness; node color: topic cluster. Generated by VOSviewer[15]



7 Green Industry in Educational Programs

Faculty of Behavioral and Social Sciences

BSc | *Psychology; Sociology*
MSc | *Environmental Psychology; Sociology*

Faculty of Economics and Business

BSc | *Econometrics and Operations Research, Economics and Business Economics*
MSc | *Small Business & Entrepreneurship (in collaboration with the University College Groningen); Technology Based Entrepreneurship (in collaboration with University College Groningen); Supply Chain Management; Technology and Operations Management; Marketing; Economics; Econometrics, Operations Research and Actuarial Studies*

Faculty of Law

LLB | *International and European Law*
LLM | *Energy and Climate Law; Advanced LLM in Energy Law (joint degree with the Universities of Oslo (Norway), Aberdeen (United Kingdom) and Copenhagen (Denmark))*

Faculty of Science and Engineering

BSc | *Chemistry; Chemical Engineering; Computing Science; Industrial Engineering and Management; Life Sciences and Technology; Pharmacy*
MSc | *Chemical Engineering; Chemistry (Tracks Advanced Materials / Catalysis and Green Chemistry / Science, Business and Policy); Honours Master High-Tech Systems and Materials; Computing Science (Tracks Data Science and Systems Complexity / Science, Business and Policy / Software Engineering and Distributed Systems); Energy and Environmental Sciences; Industrial Engineering and Management (Tracks Production Technology and Logistics / Product and Process Technology); Mechanical Engineering (Tracks Advanced Instrumentation / Smart Factories / Materials for Mechanical Engineering / Process Design for Energy Systems); Nanoscience; Pharmacy; Water Technology*

Faculty of Spatial Sciences

BSc | *Spatial Planning and Design*
MSc | *Environmental and Infrastructure Planning; Economic Geography*

University College Groningen

BSc | *Innovation and Entrepreneurship*
MSc | *Small Business & Entrepreneurship (in collaboration with the Faculty of Economics and Business); Technology Based Entrepreneurship (in collaboration with the Faculty of Science and Engineering)*

Campus Fryslân

BSc | *Global Responsibility and Leadership*
MSc | *Sustainable Entrepreneurship*

8 Research Centers & Organizations

Internal Research Centers & Organizations

Centre for Energy Economics Research

rug.nl/ceer

The Centre for Energy Economics Research (CEER) conducts research on various topics within energy economics. These include: energy business, energy markets, consumer behavior regarding energy, macroeconomic effects of developments in energy markets and government policies towards the energy industry.

Centre of Energy Law and Sustainability

rug.nl/rechten/onderzoek/expertisecentra/gcels

Within the Faculty of Law of the University of Groningen, the Groningen Centre of Energy Law and Sustainability (GCELS) coordinates all research involving (parts of) the energy sector. Its research covers the entire energy chain ("from well to burner tip") and includes all legislation and regulation applying to the production, transmission and supply of energy, the promotion of renewable energy sources, the need to secure energy supply as well as issues concerning climate change and environmental protection.

Centre of Entrepreneurship

rug.nl/society-business/centre-for-entrepreneurship

University of Groningen Centre of Entrepreneurship (UGCE) is the academic player in the area of innovation and entrepreneurship in the north-eastern region of the Netherlands. UGCE contributes to the valorization of the university knowledge by developing new methods to enhance entrepreneurial / business competencies. We aim to support existing companies and start-ups, contributing to the economic development of firms and regions. Our instruments for that include student consultancy projects, competencies for innovation instruments, diverse forms of trainings and VentureLab, which is a business growth accelerator for high-tech well-established companies that offers business development support for technology-based start-ups.

Centre for Sustainable Entrepreneurship

rug.nl/cf/centre-for-sustainable-entrepreneurship

The mission and vision of the Centre for Sustainable Entrepreneurship (CSE) is to preserve the planet for future generations through successful sustainable entrepreneurship. CSE provides students, business leaders, policymakers, and academic scholars with the knowledge and competencies they need to make sustainable entrepreneurship successful. CSE offers a full-time master program as well as the knowledge needed to successfully design, implement and manage sustainable enterprises. Students in the master program actively engage with regional stakeholders in order to identify business and policy challenges in the transition towards a circular economy. CSE offers a wide range of in-depth research projects, policy instruments/monitors, and best practices including sustainable leadership, organization, collaboration and performance. CSE also offers the Sustainable Startup Academy for students, the circular 11-city tour for citizens and science lectures on sustainable entrepreneurship in a circular economy for regional entrepreneurs and policy-makers.

CogniGron

rug.nl/research/fse/cognitive-systems-and-materials

Groningen Cognitive systems and Materials Center (CogniGron) is a research initiative that aims to address fundamental questions of relevance for developing materials and systems for cognitive computing. The center is embedded in the Faculty of Science and Engineering and was created to provide structure, coherence and visibility to a joint research program that comprises researchers from materials science, physics, chemistry, mathematics, computer science and artificial intelligence. The research program aims to generate focus and critical mass to address the challenge of including new functional materials in the design of the new generation of cognitive computers, focusing on the fundamental research aspects.

Green Office Groningen

rug.nl/about-us/who-are-we/sustainability/green-office

Green Office Groningen is a department of the university led by students and staff members. The Green Office coordinates and initiates projects related to sustainability at the University. We connect, inform, and inspire students and staff members about how to act more sustainable and show them why this is important. In addition, we influence policy and business operations to ensure that they are more sustainable. Our goal is to make sustainability an integral part of the University of Groningen and to keep sustainability on the agenda.

Groningen Engineering Business Center

rug.nl/fse/engineering/business-gebc

The Groningen Engineering Business Center (GEBC) is a collaboration between industry and the Faculty of Science and Engineering of the University of Groningen to develop a sustainable and consistent relationship in the field of engineering. Our aim is to encourage and facilitate developments, research and innovation of companies that are located in the Northern Netherlands. GEBC is part of the Groningen Engineering Center (GEC), a unique platform for interdisciplinary engineering research and education, gathering scientists who bridge fundamental sciences and applications in a comprehensive environment.

Groningen Energy and Sustainability Programme

rug.nl/research/energy/collaboration

The Groningen Energy and Sustainability Programme (GESP) is the university platform for discussing and coordinating energy-related research and education. The objective of GESP is to foster interdisciplinary collaboration, facilitate the cooperation with external parties (such as industry and public authorities) and advise the board of faculties and the university on strategic decisions regarding energy-related research, education and dissemination of research results.

Northern Knowledge

northernknowledge.nl

Northern Knowledge is a 'knowledge transfer office' for knowledge institutes and companies in the northern region of the Netherlands. For this purpose, the UG, the UMCG and the Hanze UAS Groningen have joined forces in the areas of valorization and entrepreneurship. Northern Knowledge's services focus on patent management, expertise in the area of intellectual property, screening and scouting, facilitating business people and supporting business development.

External Organizations

Bio Economy Region Northern Netherlands

bernn.nl

Bio Economy Region Northern Netherlands (BERNN) is a collaboration between the four Northern Universities of Applied Sciences and the University of Groningen, with the aim of allowing the Northern Netherlands to maintain and further expand its position within the Biobased Economy.

Campus Groningen

campus.groningen.nl

Campus Groningen is the innovation engine for the northern region of the Netherlands. It targets public-private partnerships – with links to the region – that focus on growth. The campus has two adjacent locations, the Healthy Aging Campus and the Zernike Campus Groningen, both of which are managed as a single ecosystem for the purposes of collaboration. It is a place where knowledge institutions, companies, facility providers and students can encounter one another. The natural growth of this campus is sustained by ongoing increases in scale, by the professionalization of business park management, by the acquisition of companies and by attracting large investment funds.

Carduso Capital

cardusocapital.com

Carduso Capital wants to increase the value creation and transformation of knowledge into profitable technology companies not just by the participation with venture capital, but also by giving a proactive management support and the use of its broad international network. The University of Groningen is a co-initiator of Carduso Capital, which invests mainly in technology companies from three areas of interest: life sciences, energy and sustainable society.

Chemport Europe

chemport.eu

Chemport is an ecosystem in the Northern Netherlands in which companies that are committed to developing a greener chemical sector can flourish. Companies, knowledge institutes and government together create the conditions for transformation and green growth of the chemical industry.

Innolab Chemistry

innolabchemistry.com

To bring projects from research toward proofs of concept, partners at Campus Groningen envisaged a laboratory place for new ventures. Innolab Chemistry stimulates and supports entrepreneurship, and facilitates innovative initiatives. Besides offering laboratory facilities, business support is offered in the fields of business development, business strategy, intellectual property and patenting, legal aspects, budgeting, finance and risk analysis. The facilities of Innolab Chemistry are suitable for product development in the (bio)chemical field.

New Energy Coalition

newenergycoalition.org

New Energy Coalition (NEC) is a network and knowledge coalition that aims to contribute to a sustainable energy future and to the development of the Northern Netherlands as a leading, dynamic energy region. With this in mind, NEC develops, enhances and disseminates knowledge and expertise relating to energy, trains professionals and contributes to an excellent climate for innovation and *activities in the energy sector. NEC initiates, facilitates, coordinates and implements programs and projects, acting as a central pivot in an extensive partner network and as a driving force and discussion partner to bring organizations together.*

RUG Holding

rugholding.nl

The road from brilliant idea to flourishing business is long and difficult. The RUG Houdstermaatschappij (RHM, or RUG Holding) has supported scientists in the process of starting a business since 1996. RHM brings knowledge, experience and a broad and unique regional business network within the reach of successful young entrepreneurs and companies.

Zernike Advanced Processing

zapgroningen.nl

The Zernike Advanced Processing (ZAP) facility is a semi-industrial environment where knowledge institutions and businesses collaborate on innovative solutions for the biobased economy. Entrepreneurs contact the ZAP facility with applied research questions, and we like to use the experience of these entrepreneurs to market new biobased products or to make (chemical) processes more sustainable. This contributes to a solid region and a stronger international position. ZAP is located at EnTranCe, the Centre of Expertise Energy of Hanze University of Applied Sciences Groningen. EnTranCe is a public-private partnership that offers room for open knowledge-sharing.

9 Green Entrepreneurship at the University of Groningen

The University of Groningen employs great effort on knowledge transfer, supporting mutually beneficial collaborations between universities, businesses and the public sector and helping to translate scientific research into applications with a positive societal impact. Furthermore, it provides support and guarantees a fertile ecosystem in which entrepreneurs from a wide range of expertises can thrive. The several innovative businesses listed below play a fundamental role - both locally and globally - in the exciting and challenging path towards the development of green industries.

Albatrozz

albatrozz.eu

Albatrozz can be a performance upgrade of new and existing wind turbines. The Albatrozz is a technology to increase lift at low wind speed up to 2 times. The technology can be used to start wind turbines at lower wind speed. This results in an increase of operational hours of wind turbines and thus to a higher production of renewable energy.

BioBTX

biobtx.com

BioBTX B.V. was founded to develop efficient and effective technologies for the production of sustainable BTX. We do this out of a love for the planet we've been given and out of a passion about changing the way we look at waste.

Bioclear earth

bioclearearth.nl

For 30 years, Bioclear is recognized as a leading innovation and consultancy company in the areas of biological remediation of soils, sediments and water, ecosystem health and biological reuse and recovery technologies. Bioclear earth develops innovative solutions that are robust, cost-effective and sustainable, by exploiting the vast potential of nature's biological processes.

Biofuran Chemical Products

biofuran.com

Biofuran Chemical Products develops high value chemical materials derived from renewable resources that outperform fossil based chemicals on price, performance and sustainability. Besides the in-house development of urethane polyols, we cooperate with innovative companies that develop a broad range of chemicals, polymers and biomaterials.

CarbExplore Research

carbexplore.com

CarbExplore's team has a significant track record of both scientific and technical expertise. The group is particularly skilled in the development and characterization of enzymatically modified starches and carbohydrates with a significant role in prebiotics and functional foods.

Chicfashic

chicfashic.com

The main concept of the Chicfashic platform is to reimburse that great feeling of shopping online, but in an environmentally friendly manner. With this design, people can share and reuse clothes all over the world.

EV Biotech

evbio.tech

EV Biotech will evolve the chemical feedstock market by revolutionizing the methods of microbial cell factory strain engineering, hereby shifting the chemical market from petrochemical-based to biological-based chemical production.

Foamplant

foamplant.nl

We are on a mission to transform the foaming industry by offering the world a sustainable alternative to technical foam materials. Foamplant is your supplier of compostable foam, soil degradable foam, biobased foam or customized biodegradable foam.

Gaia Food

gaiafood.nl

We believe that insects deserve a greater role in our diet. Not only because we make a positive impact on our earth, but also because we can improve our own health. GaiaFood works on the development of insect-based sports food, meat substitutes and processing insects in bread, pasta and snacks to realize this vision.

Gecco

gecco-biotech.com

After many years of research and development at the University of Groningen, GECCO is in a unique position on the enzyme market. We developed a unique collection of enzymes and cofactors that are now finally available for you. Furthermore, you can take advantage of our extended know-how and in-house developed software to help you develop ad-hoc applications and advance your research efforts.

KNN Cellulose

knncellulose.nl

From efficient process to innovative products, KNN Cellulose BV provides cellulose-based solutions to help major industries in reducing carbon emission through circular economy.

Ocean Grazer

oceangrazer.com

At Ocean Grazer, we are convinced that hybrid energy systems will play a key part in commercial, sustainable and clean energy production. To this end, we develop novel technologies to harvest and store renewable energy offshore.

Polyganics

polyganics.com

Polyganics develops bioresorbable and biocompatible synthetic polymers for use in a range of applications driving tissue regeneration and functional patient recovery.

PolyVation

polyvation.com

PolyVation provides polymer development, custom synthesis, scale-up and GMP manufacturing services for customers developing and commercializing advanced biomedical and pharmaceutical product applications.

SeaQurrent

seaqurrent.com

Tidal and ocean currents contain a large amount of kinetic energy. SeaQurrent develops a completely new approach for harvesting this energy. Our patented multi-wing TidalKite™ makes it possible to generate clean electricity from shallow (and deep) low velocity tidal and ocean currents with an efficiency rate resulting in a breakthrough of the price of electricity produced from tidal energy.

SG Papertronics

sgpapertronics.com

At Papertronics, we deliver solutions and tools to get the desired information in a short time wherever and whenever you need it. We specialize in the development of on-site chemical analysis, bringing the lab to you.

Sustainable Buildings

sustainablebuildings.nl

Sustainable Buildings is more than an initiative or a company. It is a philosophy aimed at making buildings energy-efficient. Our Mission is to provide buildings with an innovative and affordable cloud-based energy management system to accelerate their transition to sustainability.

Syncom

syncom.eu

Syncom is a global leader assisting the pharmaceutical and biotech industries on their drug discovery and development programs. Syncom has an excellent track record dating back to the foundation of the company in 1988. We count both leading global pharmaceutical companies and small virtual start up companies among our clients. In addition to our pharma activities we serve the diagnostic, fine chemical, electronic and pigment industries as well.

10 Industry Relations Office

The University of Groningen (UG) distinguishes itself, both at the national and international level, by its strong links between education and research, as well as by providing a fertile environment for innovation. This offers ample opportunities for multidisciplinary and interdisciplinary projects with great societal impact. Cooperation with partners is a fundamental aspect to pave the way towards new developments, in line with the green industries' concepts of sustainability and circularity. The UG's **Industry Relations** team works to establish links between University and other parties. An important step of this process is that the partners – each on the basis of their own core qualities and core values – formulate a common goal to tackle societal challenges. This goal is then translated into a sustainable collaboration program. The collaboration may focus on research, education, talent development or societal impact. This involves aspects such as knowledge sharing, question-driven fundamental research, or the translation of knowledge into products or services. It could also include internal training programs, student engagement and the establishment of new networking organizations. We are looking forward to talk to your organization about such possibilities, so if you have questions, comments or suggestions please get in touch with the team of Industry Relations.

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Our Portfolios & Innovation Agendas

Examples from research practice can be found in our portfolios *Big Data*, *Digital Society* and *Towards a Circular Economy*. Furthermore, an innovation agenda on the *Smart Mobility* theme and an *Academic Roadmap for Smart Industries* are available.

university of groningen

With this innovation agenda, we intend to present our research carried out in the Green Industry theme, as well as current collaborations and our ambitions for future joint projects with relevant stakeholders. We invite companies, nonprofit organizations and governmental organizations to contact us and explore opportunities to connect, find synergies and together contribute to the development of the green industries of the future.

Industry Relations
Connecting to society