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TNO report

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Research Program 2019 Topsector Chemistry

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1.1 Summary

In line with the needs of society and specifically the chemical industry and with the ambitions of the Topsector Chemistry, TNO's Demand Driven program Sustainable Chemical Industry focuses on developing technology and new business models in three mission-driven Public Private Partnerships being Biorizon, Voltachem and Brightlands Materials Center, whilst exploring novel topics like digitization and recycling in relation to these partnerships. We will, for the period 2019-2022, continue to strengthen these partnerships and further embed them in regional, national and international innovation ecosystems.

Biorizon
In 2022 Biorizon will have demonstrated the Waste2Aromatics and Diels-Alder technologies at TRL6/7 for a number of relevant waste streams and aromatic products respectively. To this end, process installations will be developed and deployed in 2019 as stepping stone to the design, construction and use of the pilot plants.

VoltaChem
The VoltaChem program line Power-2-Chemicals aims to have demonstrated by 2022 paired electrosynthesis of key plastic intermediates and high value chemicals together with industry and academia. End of 2019 we will have a continuous flow reactor available on bench-scale (TRL4) for paired electrosynthesis of chemical building blocks. Furthermore we will expand our network and equipment and know-how base. The program is closely aligned to the Demand Driven program Industrial Electrification and CCUS that has a much broader focus on industrial electrification as a whole.

Brightlands Materials Center
In 2022, the program line Sustainable Buildings will have developed a range of materials that contribute to reducing the energy consumption of buildings, and to generation of renewable energy on-site. Examples of such materials are adaptive solar control coatings for application on glass and polymer foils/sheets, nanocomposite polymer foils/sheets for adaptive infrared light regulation, and nanocomposite polymer foils for light management in solar modules. The developed materials will be integrated in their respective products/modules, and demonstrated as system prototype in an operational environment (TRL 7). In 2019, we will scale up our coating formulations and establish a pilot infrastructure for the application of solar control coatings to glass sheets (size 40x40 cm) to produce pilot scale demonstrator products, and infrastructure for performance validation of the product demonstrators, e.g. set-ups for accelerated life time performance testing. Furthermore, current products, i.e. thermochromic nanopigments and composites, and high refractive index polymers foils, will be optimized at lab scale, and new products will be developed.

In 2022, the program line Lightweight Automotive aims to have developed and demonstrated physics based material models as life prediction tool to optimize lightweight thermoplastic composites including design rules for use in applications. Also technology and infrastructure to recycle these materials into Long-Fiber-Thermoplastic compounds for structural applications will be developed.

For 2019, the Fieldlab Thermoplastic Composites will be opened on the new location at the Brightlands Chemelot Campus, and develop a hybrid demonstrator, with newly developed equipment and material.

Additionally in this VP we will explore in 2019 the potential of photo chemistry, building on results from the Early Research Program Energy Conversion & Storage. In 2019, plasmon catalysts will be tailored for reduction of CO_2 to CO using sunlight as energy source, and concepts for reactors for plasmon catalysis using sunlight to drive conversions will be developed.

1.2 Short description

The long term goal of the total Demand Driven program “Sustainable Chemical Industry” is to establish proven solutions that provides feedstock flexibility, efficient processing and improved product functionality to the chemical industry. The program is mission-driven and organized in Public Private Partnerships that are embedded in regional, national and international ecosystems. These PPP’s are:

Biorizon
The long-term goal for Biorizon is to enable commercial production of bio-aromatics. 2025 marks the point at the horizon of the first commercial plant, with many to follow. The Biorizon program is currently focused on progressing the technology toward that point by climbing the TRL-ladder for two selected aromatic targets. In 2021 a multi-purpose pilot plant (TRL6/7) will be established to demonstrate the versatile Diels-Alder based technology. In the meantime, the program is applying the Diels-Alder toolbox to other aromatic targets, which will be tested at pilot scale from 2022 onwards. To be able to attain these goals, knowledge is required about the products in which the aromatics can be applied, their markets and the required specifications. Furthermore, process technology, catalysis and organic chemistry will be further developed for this purpose.

VoltaChem
In the program line Power-2-Chemicals of the Shared Innovation Program VoltaChem we focus on the electrochemical production of intermediates for plastics. The scientific focus will be on the development of paired electrosynthesis as a platform technology for highly efficient production of chemicals at both electrodes to achieve better business cases. Enabling expertise that will be further developed together with our partners are electrochemistry, electrocatalysis, electrochemical reactor technology, membrane technology, electrochemical engineering, downstream processing integration and system design. The goal of this program line for 2022 is to have demonstrated this technology in at least two pilots at industrial scale in close collaboration with academia and industry labs and in parallel to have realized a set-up of complete screening and piloting testing infrastructure that will accelerate further development towards commercial implementation.

Brightlands Materials Center
The program line Sustainable Buildings contributes to transform current energy consuming buildings into net suppliers of energy. It is focused on developing materials that enables reduction of energy consumption and efficient generation of renewable energy on site. Coatings for application on glass and polymer foils will be developed as well as nanocomposite polymer foils. Functionality of the materials are adaptive solar control coatings for window glazing, IR regulating nanocomposite foils for safety glass, and nanocomposite foils for light management

in solar modules. Synthesis, surface modification and processing of nanoparticles into solution processed coatings or polymer sheets and foils are required core competences. In 2022, we established both pilot infrastructures to produce pilot scale demonstrator products, and infrastructure for performance validation of the product demonstrators.
The program line Lightweight Automotive contributes to sustainable (automotive) mobility by developing innovative solutions based on expertise in the field of polymeric materials. An important goal is to develop multi-scale, physics based material models that lead to lighter designs, and reduction of cost and time needed for testing and validation of continuous fiber reinforced thermoplastic composites and hybrids. In 2022 we aim to have validated models including effects as interface fracture, long-term behavior, impact after aging and process induced properties supported by newly developed tests. Another goal is to develop processing and modelling recycling technologies for thermoplastic composites coming from post-industrial and from post-consumer mono-material waste streams. For 2022, the interaction of size reduction method, material behavior and processing in series processes as injection and compression molding is used to recycle this waste as Long-Fiber-Thermoplastic compounds with controlled specifications and bandwidth.

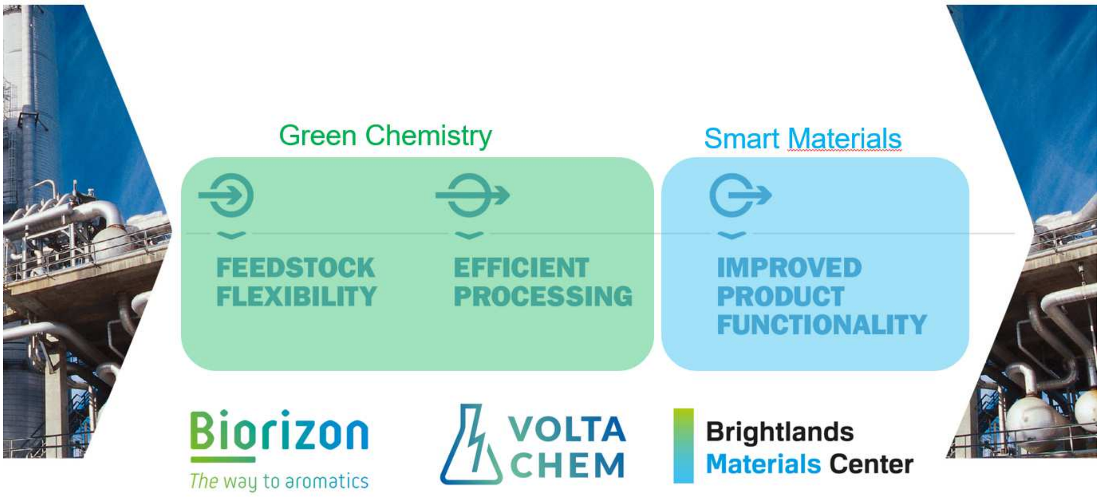
1.3 Results 2019

The challenge of the Dutch Topsector Chemistry is to contribute to the societal transition towards a carbondioxide neutral circular economy with sustainable energy sources in the coming 30 years, whilst remaining competitive during this transition. Therefore, the goal that the Topsector has set itself in its KIA is: “in 2050 The Netherlands is known as *the* country for green & sustainable chemistry” and “smart materials with high added value whilst providing smart solutions”. This context and goal, the continuous discussion with our stakeholders and our competences and facilities together determine the focus of the program Sustainable Chemical Industry at TNO.
The Topsector has identified high-level focal themes that will contribute to its goals, based on existing roadmaps, societal challenges and key enabling technologies. The themes “Waarde uit Biomassa”, “Electrochemical Conversion & Materials” and “Soft Advanced Materials” and the “Go-Chem” initiative form the platform for the three mission-driven Public Private Partnerships (Biorizon, Voltachem and Brightlands Materials Center) that TNO has set up with public and private stakeholders. In 2019 the program Sustainable Chemical Industry will further strengthen and expand these three existing mission-driven Public Private Partnerships (PPP), further embed them in regional, national and international innovation ecosystems, and at the same time explore new or enabling topics that will add to their strengths.

The program will again contribute in 2019 to:

a) Intensified ***triple-helix collaborations*** with industry, academia, RTO’s and regions in the Joint Innovation Centres.
b) Realization of ***piloting infrastructure*** for the key technologies (electrochemistry, Diels-Alder chemistry and nanoparticle synthesis & surface functionalization).
c) Delivery of prototypes of ***sustainable chemical building blocks and smart materials***.
d) ***Strengthened knowledge & IP position*** in the fields of green & sustainable chemistry and smart materials in order to provide industry with competitive solutions.

The below figure indicates the positioning of the three PPP's.



More specific the expected results for the specific programs lines are:

Biorizon
For 2019 the focus of the Biorizon program is on the realization of several proof of concepts at TRL5.

- For the Waste2Aromatics program attention goes out to proving continuous conversion of bio-slurry's as manure and primary sludge into furfural (and levulinic acid). This will culminate in a blueprint for a pilot plant.
- For the Diels-Alder program several process installations will be established with which proof of concept for key technologies (Diels-Alder, ring-opening, hydrolysis, oxidation) can be obtained at TRL5.

The process installations will be used to produce samples of 5-20 kg, for further application testing by industrial partners in resins, lubricants, polyurethanes. Furthermore, input to the design of the multi-purpose pilot plant will be generated. Finally, in 2019 the scope of aromatic targets accessible through Diels-Alder chemistry will be expanded by exploring different starting materials (furans and dienophiles) at TRL1-3.
In 2019 TNO will continue the collaboration with WFBR, Utrecht University and Avantium on the technology development. In addition, TNO will further expand the number of industrial partners that aim to apply MPA and HMA in their products.

VoltaChem
For 2019, the focus is on three aims. These aims are:

- Further expansion of the VoltaChem industrial community and research network.
- Electrochemical synthesis:
  - Electrochemical continuous flow reactor design for efficient paired electrosynthesis at TRL 4.
- Enabling technology development:
  - Expanding electrochemical toolbox and infrastructure.
  - Concept development for integrated downstream processing (DSP) and mediator retention.
  - Quick scan methodology for selection of electrochemical membranes, electrodes and catalysts.
  - Tools for system design and scale-up.

We expect to have proven at least 2 new electro-organic selective oxidation/reduction reactions at proof of principle level, one process intensification concept related to electrochemical reactor design validated and 1 paired continuous flow electrosynthesis at TRL 4 together with our partners.

Brightlands Materials Center
Program line Sustainable Buildings:
- Full optimization of adaptive solar control coatings on glass at laboratory scale, and design for scale up to pilot scale established.
- New concepts for solar control coatings/foils/sheets established (together with Hasselt University).
- Reproducible lab-scale production of infrared regulating polymer foils, and design for scale up to pilot scale established.
- Strengthening and expansion of current IP portfolio on infrared regulating/solar control coatings/foils/sheets.
- Demonstration of performance of light management foil in PV module.
- Infrastructure (test buildings) for performance validation of solar control glazing established (together with Zuyd Hogeschool).

Program line Lightweight Automotive:
For 2019, the Fieldlab Thermoplastic Composites will come into operation on the new location at the Brightlands Chemelot Campus. This infrastructure will be further expanded and used to validate developed technologies, test methods and modeling concepts. Gained knowledge will be translated and added in design guides. Furthermore, a hybrid thermoplastic composite demonstrator, with newly developed equipment and material will be developed.
The developed recycling technology from Thermoplastic Composites to Long Fiber Thermoplastc compounds will be expanded to more polymer systems, and will be evaluated on larger scale equipment. Collaboration with unit CEE and the Topsector HTSM will be intensified, and cooperation with UT and TPRC reinforced.

Photon Chemistry
To date TNO developed in the Early Research Program Energy Conversion & Storage the concept of plasmon catalysis to convert carbon dioxide to methane using terrestrial sunlight as energy source for the process. Within this VP we will further look into this topic. Because of the more favorable business case, we will tune the selectivity of the developed plasmonic catalysts to carbon monoxide (syngas) in 2019. Furthermore, in 2019 we will develop projects that enable the development of a suited reactor concept for plasmon catalytic conversions, ultimately focusing on a pilot-scale set-up that enables a detailed techno-economic feasibility study. In 2019, plasmon catalysis will be tailored for reduction of CO_2 to CO using sunlight as energy source, and concepts for reactors for plasmon catalysis using sunlight to drive conversions will be developed.

1.4 Dynamics

Biorizon
No changes are foreseen concerning technology development, IP position, collaborations or organizational compared to the plan for 2018-2021. When zooming in on the technologies being developed within the Waste2Aromatics program, one can observe that TNO has divided attention over C5-sugar solutions to be treated with the bi-phasic reactor technology and bio-slurry’s (like manure) that cannot be treated likewise, but require a different approach: a similar less complex technology, without the use of a solvent during conversion.

VoltaChem
In 2018 the new Demand Driven program (VP) Industrial Electrification and CCUS has been started that taps into the VoltaChem platform. This new VP focuses on the combination of industrial electrification and carbon capture and storage, mostly focusing on production of commodity chemicals to achieve impact in decarbonization of the industry. Within the VP Sustainable Chemical Industry, we will focus even more on the electrosynthesis of key intermediates for novel plastics and high value chemicals (novel chemistry), thereby leveraging on the ongoing activities in the program as a whole.

Brightlands Materials Center
For program line Sustainable Buildings the technology development is on plan for 2018-2022. IP position needs to be further strengthened and expanded to form a solid base for the shared research program. Strategic collaboration ongoing with Zuyd Hogeschool and Hasselt University on development and performance validation of solar control/adaptive IR regulating products. Collaborations with industrial partners via subsidized projects on plan. Active participation in regional sustainable energy discussions ongoing (e.g. LEKTA, PALET).

Focus is created in the program line Lightweight Automotive by changing Integrated Electronics into a project within the Predictive Materials Performance topic that concentrates on adhesion, over-molding and life prediction. A first new test method and modeling concept on adhesion is set-up, and under evaluation. Due to change of partners and related project content, extension of the Fieldlab project Thermoplastic Composites is approved till 2020. This relates in particular to technology and material development from the post-industrial waste stream.

2 Industrial Electrification and CCUS

2.1 Summary

In 2018 a new Demand Driven program (VP) Industrial Electrification and CCUS was initiated by TNO, focusing on the unique combination of industrial electrification and carbon capture, utilization and storage. The increasing amounts of renewable wind and solar derived electrical energy offer great opportunities for the industrial production of green hydrogen and the conversion of renewable raw materials (e.g. biomass, CO_2) to added value chemicals and fuels. This program aims at the development and piloting of novel Industrial Electrification and CCUS technologies and relevant business models. The focus of the program is on the unique combination of electrification with biomass conversion and the integration of industrial electrification with carbon capture and utilization.

The previous year was aimed at determining the focus of the program, identifying research questions for the coming years, starting up the new activities, building necessary research infrastructure and basic know-how with respect to Solid Oxide Electrolysis and high temperature heating, and coupling the program structure to the existing frameworks of VoltaChem and CCUS activities. In 2019, we will continue with the R&D that has started in the previous year and will connect to national and international stakeholders for collaboration. Focus of the activities in 2019 and the expected results will be:

- High-temperature cracking for decarbonizing ethylene production. First conceptual design of experimental facilities.
- Solid Oxide Electrolysis technology and its integration in industry. Manufacturing capability for 10x10 cm SOEC’s available.
- Paired electrosynthesis of biobased feedstock and CO_2. Proof of concept of paired electrochemical CO_2 and biobased conversion at TRL 3.
- Integrated value chains for CO_2 capture and conversion. Full CCUS value chain assessment towards valuable products and associated R&D plan available.
- Value chain development for fuels, fertilizers and materials (plastics, steel). Worldwide and regional models tested and validated.

Furthermore, we will focus on developing industrial Fieldlabs in the most relevant national energy & industry clusters. In these Fieldlabs above developments, amongst others, can be further piloted and brought towards demonstration together with industry and public stakeholders. Through this approach we aim to accelerate the development and implementation of results towards 2022, so that our contribution to the 2030 and 2050 climate targets is maximized.

2.2 Short description

At the Paris climate conference (COP21) in December 2015, 195 countries adopted the first-ever universal, legally binding global climate deal. Based on this agreement, the Dutch government has decided in 2017 to cut greenhouse gas emissions by 49% in 2030 and by 80-95% in 2050. This will be a huge challenge for the heavy (chemical) industry and electricity sectors. At the same time this will provide an opportunity for high-tech chemistry and equipment supply companies to develop and market new innovative solutions.

Industrial Electrification and CCUS are important solution directions to decarbonise the industry, as also identified by the VNCI in its roadmap 2050 and by the Topsectors Chemistry and Energy and the Ministry of Economic Affairs and Climate. The increasing amounts of renewable wind and solar derived electrical energy offers great opportunities for the industrial production of green hydrogen and the conversion of renewable raw materials (e.g. biomass, CO_2) to added value chemicals and fuels. Crucial for the energy system of the future is the integration with energy storage and conversion to balance the energy system. This program aims for the continuation of development and piloting of relevant industrial electrification technology and relevant business models. The focus of the program is on the combination of electrification with biomass conversion and the integration of industrial electrification with carbon capture and utilization. For the latter, the development of cost effective industrial applicable carbon capture and storage chains are of relevance.

To accelerate development and implementation of Industrial Electrification and CCUS in the Dutch context, two parallel tracks are being pursued towards 2022:

1. *Support of piloting in large Dutch industrial clusters by means of industrial Fieldlabs*
   Implementation of industrial Fieldlabs in the relevant energy & industry clusters (Rotterdam-Moerdijk, Brightlands-Chemelot, Groningen, Amsterdam-Ijmuiden, Zeeland).

2. *Co-creation of electrification and CCUS knowledge and technology:*
   a) *High temperature heat based on renewable electricity:* development of technology for direct use of electricity in high-temperature processes.
   b) *Renewable hydrogen production and conversion*: lowering total system costs, dealing with flexibility and efficient downstream conversion to valuable products.
   c) *Direct electrochemical conversion*: efficient conversion of renewable feedstock (biobased and CO_2) towards chemical building blocks and energy carriers.
   d) *Direct and indirect conversion of CO_2*: development of technology for efficient CO2 valorization towards useful products to improve the business case of CCS.
   e) *Value chain integration*: development of electrification and CCUS models and scenario's for making strategic decisions in industry, energy and infrastructure.
   f) *Regulatory aspects*: analysis of necessary changes in national and international regulations to enable a cost-effective and balanced roll-out.

All activities of the program are coordinated and/or co-created with public and private partners from national and international industries, governments and ngo's. A large part of the program is implemented through the Shared Innovation Program VoltaChem, in which approximately 25 companies and institutes from the energy, chemical and equipment sectors work together on acceleration of industrial electrification. Furthermore, the program connects to relevant national and international CCUS platforms. Through these extensive collaborations we aim to accelerate the development and implementation of results towards 2022, so that our contribution to the 2030 and 2050 climate targets is maximized.

2.3 Results 2019

The activities in the VP Industrial Electrification and CCUS are defined using continuous portfolio management. Existing developments are taken further towards piloting and demonstration at industrial partners or in open industrial Fieldlabs and new developments enter the program through continuous scouting activities. Furthermore, there is continuous interaction with projects in other internal and external related programs.

The following activities will be part of the Industrial Electrification and CCUS program in 2019:

1 Support of piloting in large Dutch industrial clusters by means of industrial Fieldlabs

To accelerate the development and implementation of Industrial Electrification and CCUS processes, and thereby realize large scale CO_2 reduction in industry, a cost-effective and efficient means for scaling up and testing new technologies is needed. Validation of technologies must happen at an industrially relevant scale in a practical environment. This allows for continuous development towards commercialization while verifying business cases and bringing together input from various stakeholders: end users, technology providers, equipment manufacturers, and knowledge institutes.

Early 2018, an assessment was made of the potential for industrial Fieldlabs in multiple energy & industry clusters in The Netherlands. Based on this assessment, three dedicated Fieldlab developments were started together with regional stakeholders: Brightlands Sustainable Technology Center (cluster Geleen-Chemelot), Fieldlab Industrial Electrification (cluster Rotterdam-Moerdijk) and MW Electrolyzer Test Centre (cluster Groningen-Eemsdelta). The assessment of their individual feasibility is currently still ongoing and will be continued in 2019.

Specific activities for 2019:
- Support in further development of the mentioned industrial Fieldlabs together with partners.
- Start first R&D and piloting activities in initiated industrial Fieldlabs.

2a High temperature heat based on renewable electricity: Electric cracking

In 2017 the E-match project identified that electrification of ethylene production could have a huge potential in the energy transition. In this study it was concluded that high temperature Power-to-Heat technologies (> 200 ° C) should be developed and implemented to tap into the CO_2 reduction potential that industrial electrification could bring in North Western Europe. Electric cracking is such an option which will make ethylene production more sustainable. This option has recently attracted attention from industry, which had led to renewed investigations at VoltaChem/TNO in 2018. These investigations involve determining of the patent landscape, key R&D questions and making a first conceptual design of experimental facilities and will be taken further in 2019.

Specific activities for 2019:
- Initiate research activities in the field of electric cracking based on the research questions that are identified together with industry before end of 2018.

2b Renewable hydrogen production and conversion: Solid Oxide Electrolysis

For green hydrogen production (Power-2-Hydrogen) multiple technologies can be considered. In order of technology maturity these are: Alkaline water electrolysis, PEM (Polymer Electrolyte Membrane) electrolysis, SOE (Solid Oxide Electrolysis) and AEM (Anion Exchange Membrane) electrolysis. Although, we consider all types within the VoltaChem framework, in the VP Industrial Electrification and CCUS we focus only on SOE due to its fit with industrial processes and its potential for CO_2 utilization.

SOE technology is seen as the best technology for industrial hydrogen production, because of its high efficiency and potential for heat integration with industrial chemical processes like production of ammonia and methanol. Also, the technology can also be used for direct reduction of CO_2 towards CO and for tuning the composition of syngas through co-electrolysis towards desired C-H-O ratio's. This has the potential to enhance further reactions towards high-value chemical products like methanol, DME and methane, and is thus a key ingredient for Industrial Electrification and CCUS. In 2018 the first step was made in realizing a SOE cell fabrication line and test infrastructure, which will be used for research purposes in 2019

Specific activities for 2019:
- Research on increasing lifetime of SOEC's towards voltage losses of < 0,2%/1000 hours and costs towards < 1000€ /kW.
- Scale up SOE cell manufacturing towards larger capacity and cell dimensions (10x10 cm).
- Investigate integration of SOE in existing industrial infrastructure and conversion processes.

2c Direct electrochemical conversion: Electrosynthesis using biobased and CO_2 feedstocks

In this research, electrosynthesis is used for direct conversion of renewable feedstock (biobased and CO_2) towards chemical building blocks and energy carriers using renewable electricity. The activities focus on developing chemical showcases together with industry and regional networks related to electrochemical synthesis of specialty chemicals (Power-2-Specialties) and commodity intermediates (Power-to-Commodities). The objective is to transform knowledge from TNO, partner universities and fundamental research institutes from TRL3-4 (labscale proof of principle) to TRL 5-6 (benchscale proof of concept). In 2018 first proof of principle research was completed on multiphase paired electrosynthesis and additional lab infrastructure was erected. In 2019 this research will be continued towards showing fully continuous paired electrosynthesis of biobased feedstock and CO_2.

Specific activities for 2019:
- Expansion of knowledge base on electrochemistry and electrochemical engineering employing selected specialty and commodity showcases together with partners.
- Development optimal reactor configurations for multi-phase electrochemical reactions.
- Further development of paired electrosynthesis using biobased and CO_2 electroconversion towards TRL3.

2d Direct and indirect conversion of CO_2: Capture and conversion technologies

In this work, technology and methodologies are developed for efficient CO_2 capture and valorization towards useful products to improve the business case of CCS. The full value chain of CO_2 capture and consecutive direct and indirect conversion towards valuable products should be considered, including integration options. Especially decentral applications, like the use of CO_2 capture at waste incinerators, warrant extra attention.

Therefore, activities in 2018 focused on de-risking CO_2 capture at waste incinerators through identifying and minimizing aerosol based emissions and on developing new techniques to reduce capture solvent degeneration. In 2019 the whole value chain of CCUS will be considered, including CCU options like technologies that are being developed in 2b (SOE) and 2c (direct electrochemical conversion), and the focus for additional CCUS work for this specific program will be determined.

Specific activities for 2019:
- Continue research on aerosol based emissions and capture solvent degeneration with focus on application in waste incinerator plants and CO_2 point sources.
- Full CCUS value chain assessment towards valuable products using renewable energy to determine focus of R&D activities in the coming years.

2e/f Value chain integration and regulatory aspects: System model development

It is important to consider novel technologies in the context of the energy and feedstock transition. For the analysis of the context of industrial electrification, it is essential to take into account the complete supply chain from feedstock to production, distribution and application of the chemicals. Besides this, it is important not to limit the scope to Western Europe, but to analyze how global energy supply and production of energy carriers and feedstocks influence the Western European market. Both energy sector and the chemical industry are rather (more and more) global markets.

In 2018 a first version of a top-down system model was developed, based on high-level electrification scenario’s, in combination with a business case calculation tool for novel technology developments. In these models, multiple technological options and economic aspects were taken into account to be able to analyze worldwide value chains towards fuels, fertilizers and materials (plastics, metals) and calculate the impact of changes in feedstocks, energy sources, product demands or applied technologies on regional industrial clusters. This model will be further improved and utilized for analysis in 2019.

Specific activities for 2019:
- Improvement of the top-down system model and business case tooling based on stakeholder feedback. We expect that expanding the business case tooling with the feature “dependent technological developments” (e.g. product and infrastructure) will improve the decision making on the matters with complex dependencies significantly.
- Application of the improved top-down system model and business case tooling on large chemical clusters to identify bottlenecks as identified by the model and preferred technology development pathways and to trigger piloting and demonstration activities.
- Expand our value chain tooling by economic impact assessment methods. Impact assessment methods (like input-output analysis) can relate specific sectoral changes (e.g. chemical industry) to changes in other sectors (e.g.

energy or other industrial sectors), and furthermore indicate the impact of these sectoral changes on several macro-economic indicators.

- Assessment of required adaptations to regulatory aspects due to macro-economic changes. This allows governments to develop regulations that facilitate transition.

Scouting activities

Next to the RD&I work that has already been programmed in multi-year activities, we keep looking externally for novel technologies and methodologies that help accelerating Industrial Electrification and CCUS. To be able to assess the value of such novel external developments, we employ a continuous technology scouting activity and start new scouting projects together with our partners on a regular basis. When assessed positively, these activities can be taken further in the next year as larger projects.

Collaboration with other VP's

There is a close connection with other VP's that focus on related topics which are of relevance for the work in this VP:

- TNO VP System Integration (Unit ECN part of TNO): Energy and feedstock system integration.
- TNO VP Geo-Energy (Unit ECN part of TNO): CCUS, blue hydrogen.
- TNO VP Energy & Industry (Unit ECN part of TNO): Efficiency, heat integration, industrial hydrogen.
- TNO VP Hydrogen (Unit ECN part of TNO): All aspects of the hydrogen economy.
- TNO VP Chemicals (Unit Industry): Biobased conversions, highly selective electrochemistry.
- TNO ERP Energy Conversion & Storage: Electrons and photons to chemicals.

External coordination and collaboration with relevant stakeholders

We coordinate and collaborate with many national and international stakeholders to accelerate implementation and to maximize impact:

- A large part of the activities is performed within the Shared Innovation Program VoltaChem, in which approximately 25 companies from the energy, chemical and equipment sectors work together on acceleration of industrial electrification. Furthermore, we connect to national and international CCUS platforms. Aim is to develop the technologies towards pilots in industrial Fieldlabs in the most important industrial energy & industry clusters (Rotterdam-Moerdijk, Brightlands-Chemelot, Groningen, Amsterdam-Ijmuiden, Zeeland).
- We collaborate with relevant academic groups in The Netherlands and abroad. In The Netherlands, focus will be on TU Delft, TU Twente, Leiden University, Utrecht university (CO_2 electrolysis, CCUS), TU Eindhoven (intensified electrolysers) and Wageningen UR (bio based conversions). Abroad, we focus on collaboration with VITO, FZ-Julich, RWTH-Aachen and Fraunhofer.
- During the program period, activities will be continuously aligned in relevant groups, amongst which are ECCM (Topsectors Chemistry, Energy and HTSM), TKI's (Chemistry, New Gas, Energy and Industry), NWA-routes energy transition, circular economy & materials and directly with the Ministry of Economic Affairs and Climate. Internationally, we will connect with IEA (OECD), Catalisti (Belgium) and DECHEMA (Germany).

- Externally, we have a close collaboration with multiple EU projects (e.g. E2C, PERFORM, H2FUTURE) and RVO projects (e.g. Power-2-FA, AMPERE). Also we will further develop the collaboration with regional activities: Port-of-Rotterdam electrification program, Brightlands Sustainable Technology Center, ENTRANCE 1MW electrolyser testing center, Hydrogen Valleys.

2.4 Dynamics

In 2018 a new VP Industrial Electrification and CCUS was initiated by TNO, focusing on the unique combination of industrial electrification and carbon capture, utilization and storage. It taps into the successful VoltaChem platform and builds on running activities in the VP's Sustainable Chemical Industry (electrochemistry), Geo Energy (CCUS) and Energy & Industry (heat integration and green hydrogen production) and the ERP Energy Storage and Conversion (integration of electrochemistry and CCS). By building on these activities and identifying new RD&I areas together with industry and academia, the program aims to accelerate development and implementation of combinations of unique technologies in the field of Industrial Electrification and CCUS in the coming years.

The previous year was aimed at determining the focus of the program, identifying research questions for the coming years, starting up the new activities, building necessary research infrastructure and basic know-how and coupling the program structure to the existing frameworks of VoltaChem and CCUS activities. In 2019, we will continue with the R&D work that has started in 2018 and start connecting to national and international stakeholders for collaboration.

3 Signature

Eindhoven, October 1st, 2018 TNO

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