

Subject

Openbare samenvatting betreffende MOOI422004

MEMO Voortgangsrapportage MOOI-regeling status november 2024

Datum

24-11-2024

Onderwerp

Voortgangsrapportage MOOI-regeling:
“Sustainable Nitrogen Chemistry by Plasma Technology for Circular Fertilizers and Fine Chemicals”

LS,

Bij deze bieden wij U aan een update van de voortgang van de MOOI422004.

“Sustainable Nitrogen Chemistry by Plasma Technology for Circular Fertilizers and Fine Chemicals”

Met status datum 1-12-2025.

Onderstaand vindt U per werkpakket een inhoudelijke voortgang.

Met vriendelijke groet,

Wilbert Derks,
Projectmanager Brightsite

Onderwerp

Openbare samenvatting MOOI422004

“Sustainable Nitrogen Chemistry by Plasma Technology for Circular Fertilizers and Fine Chemicals”

Auteurs (Authors)

Yves Creijghton, Hans Linden, Shahriah Mirpour, Dirk Vandenberg, **TNO**

Marieke Gerth, Niek den Harden, Gerard van Rooij, **UM**

Wilbert Derks, Dijana Dimitrijevic, Peter Soons, **Ebert HERA**

Doelstelling project

Dit duurzame stikstofchemieproject van MOOI heeft tot doel de energie-intensieve ammoniakproductie te omzeilen door activering van stikstofmoleculen met duurzame elektriciteit in elektrische ontladingen (plasma). Het maakt de synthese mogelijk van alternatieve, goedkopere, chemische bouwstenen zoals NO en HCN. Met de aanpak wordt circulariteit bereikt, omdat er geen fossiele inputs nodig zijn. Voor zover koolstof nodig is, valoriseert het op unieke wijze CO₂ (uit lucht of biomassa) en/of CH₄ (als primaire output van biomassahervorming of plasticrecycling). In feite wordt er procestechologie ontwikkeld die (i) een vermindering van het totale energieverbruik, (ii) een nuluitstoot van broeikasgassen, (iii) compatibiliteit met intermitterende duurzame elektriciteit, (iv) mogelijkheden voor kleinschalige lokale productie, en (v) compatibiliteit met circulaire elektriciteitsproductie biedt. koolstofstrategieën.

Het innovatieve karakter dat het huidige project onderscheidt van lopende initiatieven wordt bepaald door het kinetische voordeel dat ontstaat door het scheiden van plasma-activatie van zuivere stikstof en de oxidatie/reductie ervan door daaropvolgende menging met relevante reactanten. Het maakt het proces zuiniger dan het groene Haber Bosch en heeft het potentieel om levensvatbaar te zijn in de huidige markt

Project aim

This MOOI sustainable nitrogen chemistry project aims to circumvent energy intensive ammonia production by activation of nitrogen molecules with sustainable electricity in electrical discharges (plasma). It enables synthesis of alternative, more economical, chemical building blocks such as NO and HCN. The approach achieves circularity, as no fossil inputs are required. As far as carbon is required, it uniquely valorises CO₂ (from air or biomass) and/or CH₄ (as primary output from biomass reforming or plastic recycling). In effect, process technology is developed that offers (i) reduction of overall energy consumption, (ii) zero GHG emissions, (iii) compatibility with intermittent sustainable electricity, (iv) small scale local production opportunities, and (v) compatibility with circular carbon strategies.

The innovative nature that differentiates the current project from ongoing initiatives is defined by the kinetic advantage that arises by separating plasma activation of pure nitrogen and its oxidation/reduction by subsequent mixing with relevant reactants. It makes the process more economical than green Haber-Bosch and has the potential to be viable in the current market.

Executed activities and achieved results

Result 1: Process and system definition (literature, patent and market studies)

Result 1	Process and system definition	Start M1	End M6
	Target audience: Project team		
	Project goal: Establish overview of current state of the art and build a database of current literature and patents		
	This result will yield a literature database and "living report" on plasma state-of-the-art		
A1.1	<i>Activity 1.1: Initial process and system definition</i>		<i>IO</i>
	Lead: TNO Partners: Sitech/UM/Vitalfluid/BASF SE/Evonik/Stamicarbon	Start M1	End M6
A1.2	<i>Activity 1.2: Literature and patent overview</i>		<i>IO</i>
	Lead: TNO Partners: Sitech/UM	Start M1	End M48

A1.1

A first version of the initial process and system definition has been shared by TNO in July 2024 based on a preliminary literature study and discussions with partners in WP10 meetings (Techno economic model study for business case analyses). This document was further discussed at the consortium progress meeting in Geleen on October 10, 2024. The document needs refinements to be realized with the partners during Q4 2024.

The energy cost of plasma chemical processing at large scale is the main key performance indicator. Several types of references may be used such as the combined 'green H2' – HB process. There is a need to better motivate energy cost requirements and to uniformize the units (preferably MWh/t, kWh/kg product NO_x/HCN). It is important to take into account other factors such as transport costs which may be reduced in case of decentralized production. Beneficial features of plasma processing such as the unique possibility of instant control (in case of variations in green electricity, feed stock and/or demand of product) may be more difficult to be quantified in terms of costs.

A1.2

During the project the literature and the patent landscape will be monitored. This will be brought together in a living document. New insights from literature and patents will be used to fine tune the experimental plan and to adapt the equipment used in the project wherever necessary.

A literature data base has been set-up which is available on Ebert HERA Teams for all participating partners. A classification has been made using separate folders for NO, HCN and TEA (technical economic assessment). Because of the project focus on N₂ activation and quenching, two folders 'Nitrogen activation and recombination' and 'Quench studies' have been added.

Indirect processes, using reactant injection downstream N₂ plasma activated flow, have been investigated in the period 1960-1967 for both NO and HCN synthesis. Since better results were obtained with the direct processes (mixed gases in plasma), research activities have continued mainly using direct processes. In the Henderson (2020) paper a direct process has been used though the last author (G. Duckward) is inventor of a patent wherein the indirect process was claimed. Some literature describing nitrogen radical recombination is available and describes both the important effects of gas composition (%Ar in N₂) and pressure (Ricard et al., 1991; 2016).

Increased pressure in the range 2-4 bara has been shown to have a positive impact on NO_x yields and energy cost via the increase of the NO₂/NO based on 3-body reactions (Tsonov et al, 2023). It is important to reproduce and further validate this type of pressure dependency via experiments.

First modelling studies of very rapid quenching show options to obtain results for NO synthesis beyond thermodynamic limits (Amman and Timmins, 1966). It is important to continue this type of modelling studies (already started by UM) using more recent and better validated data sets.

Result 2: Specification and realization of a Lab and Bench scale plasma system

Result 2	Specification and realization of a Lab and Bench scale plasma system	Start M1	End M15
	Target audience: Project Team		
	Project goal: To design and construct lab and bench scale plasma reactors for experiments on both lab and bench scale to gain insight into key figures		
	This result will provide a test set-up for verification and testing plasma chemistry processes		
<i>A2.1</i>	<i>Activity 2.1: Design of lab scale plasma system</i>		<i>IO</i>
	Lead: UM Partners: Sitech/BCC/DIFFER/Vitalfluid/Evonik/Stamicarbon	Start M1	End M9
<i>A2.2</i>	<i>Activity 2.2: Realization of the lab scale plasma system</i>		<i>IO</i>
	Lead: UM	Start M4	End M9
	Partners: Sitech/BCC/DIFFER/Vitalfluid/Evonik/Stamicarbon		
<i>A2.3</i>	<i>Activity 2.3: Design bench scale plasma system</i>		<i>IO</i>
	Lead: TNO Partners: Sitech/BCC/DIFFER/Vitalfluid/Evonik/Stamicarbon	Start M4	End M12
<i>A2.4</i>	<i>Activity 2.4: Realization bench scale plasma system</i>		<i>IO</i>
	Lead: TNO Partners: Sitech/BCC/DIFFER/Vitalfluid/Evonik/Stamicarbon	Start M7	End M15

UM

A2.1

The initial proposal indicated the design and implementation of 1 lab scale reactor for both NO and HCN based experiments. As the project developed, the decision was made to move to a 2 reactor approach, with reactors specifically designed for the experimental goals. A lab scale reactor for NO based experiments, and a lab scale reactor for HCN based experiments are being realised.

A2.1: Design of the lab scale reactor(s):

For the NO based reactor an existing UM plasma reactor has been adapted for the NO experiments for the MOOI N project.

A HCN based reactor has been designed on basis of the following requirements: gas inputs (N₂, CH₄, H₂, and Ar, up to a maximum combined 40 slm), microwave power (up to 2 kW), operating pressure range (15-800 mbar), and diagnostics (FTIR).

Safe-by-design was at the forefront of the design, which includes precautions to safely produce HCN, a scrubber for safe disposal of the produced HCN, and an automated interlock system to shut down production and enter safe mode if necessary. The requirements for a safety interlock system have been specified, the design and implementation is adapted from similar interlock systems that are already operational. The reactor was designed to minimize risks of accidents, leakage, and HCN exposure, with sufficient precautions in place to safely produce HCN. The PID and technical drawing of the setup are finalized.

D2.1: The safety assessment has been completed, with a positive outlook from Brightlands, and approval of the UM internal safety group.

D2.2: The first pure N₂ plasma was created in the HCN setup on 13th of October 2025.

A2.2: Realization of the lab scale plasma system:

The HCN lab scale setup construction is nearing completion. The microwave and vacuum system are operational, which was demonstrated when the first nitrogen plasma was lighted on the 13th of October 2025. The interlock system and the FTIR diagnostic are being commissioned. A HCN scrubber for the safe disposal of HCN has been installed and is under commissioning. First HCN is expected for November 2025.

In the DIFFER setup (Microwave set up NextSF) automated pressure regulation has been installed, autotuner is ordered and will be installed shortly. Cross-field configuration for microwave coupling has been installed.

TNO

Within activity 2, TNO is responsible for the specification and realization of the benchscale plasma system. The benchscale plasma system is being constructed in the plasma lab and has passed a number of milestones. The reactor is now mechanically complete, meaning it is water and gas tight, all components have been connected, major components been tested. It is currently in the final stages of commissioning, where already it passed tests of the sensors required for safety monitoring and control. Electrical power is connected and is in final stages of testing, meaning that ignition of the first plasma is imminent.

Measures for safe handling of nitrogen products is in the engineering phase. Min/max limits of product flows have been defined and an Aspen model was devised to help understand the properties of the product output flow. A separate assessment is performed for HCN and NO_x; for HCN the possibility of burning all product in the incinerator is now considered the main scenario. In the case of NO_x the scenario of an alkaline scrubber seems the most likely. A complication with NO_x operation is the possible formation of Nitric acid (HNO₃) when liquid water is present in the reaction, which is a strong acid that could reduce lifetime of the reactor.

Results 3: Plasma nitrogen activation

Result 3	Plasma nitrogen activation	Start M7	End M42
	Target audience: project team		
	Project goal: Insights into optimal conditions and reactor parameters for nitrogen activation		
	This result will optimize the activated nitrogen formation for conversion into products		
A3.1	Activity 3.1: Microwave nitrogen activation experiments		IO
	Lead: DIFFER Partners: UM/Sitech/Vitalfluid/Evonik/Stamicarbon/BASF SE	Start M7	End M42
A3.2	Activity 3.2: Arc nitrogen activation experiments		IO
	Lead: TNO Partners: Sitech/BCC/UM/Vitalfluid/Evonik/Stamicarbon/BASF SE	Start M19	End M42
A3.3	Activity 3.3: Optical diagnostics for plasma characterization		IO
	Lead: UM Partners: DIFFER/Sitech/Vitalfluid/Evonik/Stamicarbon/BASF SE	Start M7	End M36

UM

A3.1: Crossed E-field configuration

N₂ microwave discharges show a contraction phenomenon if operated at high pressure (close to ambient pressures) which results in a high gas temperature in the center (up to 7000 K has been measured). To further improve gas flow treatment and control gas temperature to a certain extent, and to have better control over plasma activation, we have explored (and will continue doing so) a different microwave excitation scheme. Where normally the EM field in the waveguide is parallel to the flow direction, we have rotated the wave 90° so that the field is normal to the flow direction. This leads possibly to less contraction. The first results on CO₂ plasma indeed indicate that the plasma has broadened significantly, and peak gas temperature has reduced significantly from 5500 to 3500 K. However, due to this rotated field configuration the flow geometry and plasma has lost its “cylinder symmetry” has now a bilateral symmetry. This will be improved in a next design where we will use a crossed waveguide set up.

TNO

A3.2:

This activity has not started yet since it is dependent on realization of the benchscale reactor. As the benchscale reactor is continuing the commissioning phase, we are evaluating the feasibility of operation on a separate 10kW arc reactor, the so-called “mini-arc”, to mitigate further delays

UM

A3.3:

Optical diagnostics for plasma characterization

2D Raman scattering (UM)

Within this activity, UM is responsible for the development of optical diagnostics, which began according to plan (M7). Two different plasma diagnostics tools have been implemented in the plasma reactor: (i) laser diagnostics, and (ii) an ex-situ Fourier transform infrared (FTIR) spectroscopy. For the laser diagnostics, a two-dimensional (2D) Raman scattering technique has been developed for imaging temperature and gas composition from N₂ and O₂. To verify the 2D Raman technique, the temperature measured via the 2D diagnostics approach was validated against conventional 0D and 1D methods.

A Rayleigh scattering depolarization diagnostic was developed to quantify the N radical density. Measurements in the afterglow yield results that are close to those obtained with

passive methods (optical emission spectroscopy). Measurements in the plasma are difficult to interpret due to the presence of unknown species that influence the polarization of the scattered light. Experiments are planned to see if this technique can be further developed.

The precise quantification of NO using Raman spectroscopy, accuracy in temperature measurement at very high temperatures, and the suppression of plasma emission in pure N₂ plasma are the key foci that need to be addressed in the next steps.

For quantitative analysis of reaction products, ex-situ FTIR spectroscopy has been developed and is used to evaluate the desired products. More specifically, we determine the final NO_x concentration after oxygen gas injection downstream of the nitrogen plasma.

Raman Scattering Set up and Raman scattering measurements on N₂ (DIFFER)

In the past period the Raman Scattering has been totally refurbished and realigned. Hardware has now all been installed. The operational software has been totally rewritten in Python, for that a block scheme has been adopted which enables quick adaptations if necessary if different measurement procedures should be adopted. The analysis and fitting software for the N₂ rotational and vibrational spectra have been rewritten. Apart from small corrections to be implemented everything is operational now and the first non-plasma N₂ rotational spectra have been measured and analyzed successfully. A comprehensive document describing the guiding theory to analyze the rovibrational spectra has been written. Just when the first plasma measurement was planned, we had a laser malfunction (a burned out trafo), which has been repaired in the meantime.

Laser Induced Fluorescence on NO (DIFFER)

Several sessions have taken place on how to implement the Laser Induced Fluorescence (LIF) on the produced NO to measure spatially the presence of NO in the microwave flow reactor. Designs of the optical layout are finished and the hardware to perform the NO measurements is available. However, we have decided to put this on hold because we want to explore the possibility of NO detection by means of Optical Emission Spectroscopy (OES) first. The reason is that to LIF on NO is most probably very difficult to get quantitative due to interaction with the reactive species in the flow reaction. This would most certainly mean that the LIF measurement will be qualitative. The advantage of LIF remains that we can detect NO also in regions where electron excitation is low, i.e. outside the plasma regions.

Optical Emission Spectroscopy on NO (DIFFER)

Initial measurements of the spectrum of NO(γ) (wavelength region 200-300 nm) have been gathered in the plasma and downstream region of a N₂/O₂ discharge and analyzed using Specair software. It shows promise to get a good insight into the formation of NO in the plasma region, and regions where there is still excitation of this molecular band. Abel inversion algorithms are implemented to get local information which already indicates intriguing behavior of N₂ molecular band emissions and which could reveal important clues to understand the production mechanism of NO.

D3.3: A scientific publication on the developed diagnostic technique is in preparation.

Result 4: Quenching process for the formation of alternative feedstock

Result 4	Active nitrogen chemical quenching process to produce value-added feedstocks	Start M1	End M42
	Target audience: Project team and stakeholders		
	Project goal: To develop a chemical quenching process that optimizes production of desired products		
	This result will lead to an optimized performance process by maximizing process selectivity/ conversion/ efficiency for value added product formation		
<i>A4.1</i>	<i>Activity 4.1: Oxygen</i>		<i>IO</i>
	Lead: UM Partners: TNO/Sitech/Vitalfluid/Stamicarbon	Start M13	End M30
<i>A4.2</i>	<i>Activity 4.2: Methane</i>		<i>IO</i>
	Lead: UM Partners: TNO/Sitech/BCC/Evonik/BASF SE	Start M19	End M39
<i>A4.3</i>	<i>Activity 4.3: Alternative quench media</i>		<i>IO</i>
	Lead: UM Partners: TNO/Sitech/BCC/Evonik/BASF SE/Stamibon	Start M31	End M42
<i>A4.4</i>	<i>Activity 4.4: Modelling</i>		<i>IO</i>
	Lead: TNO Partners: UM	Start M1	End M42

UM

A4.1:

Active nitrogen chemical quenching process to produce value-added feedstocks

In this framework, UM is responsible for executing the experimental program in a lab-scale plasma reactor using different quench gases. For this purpose, oxygen is being used as a quench gas for the production of NO_x for fertilizers. The oxygen injection measurements started earlier than the proposed date, according to the plan (M13). In this activity, we investigate the process performance and temperature during oxygen injection into the afterglow of a nitrogen plasma. The results indicate that N-radical transport likely contributes to NO_x production downstream. However, the premixed N₂-O₂ currently outperforms downstream quenching with O₂ by a factor of two despite extensive optimization studies with many different quenching geometries. This discrepancy is likely due to operating outside the optimal conditions in power and pressure. Changes are made to the NO setup so that higher power and pressure conditions can be investigated.

A4.2+4.3:

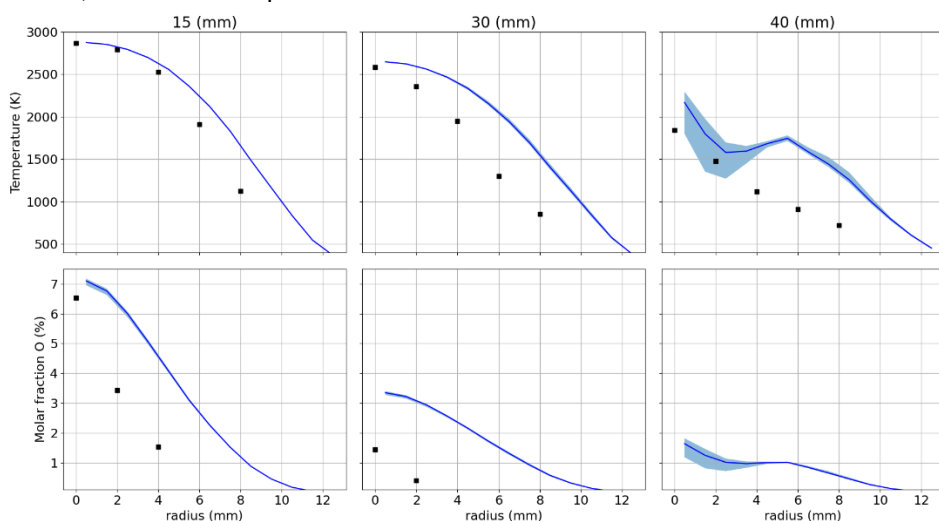
No progress on these actions to report at this moment.

TNO

A4.4

The modelling activities over the past period have consisted of CFD modelling performed by UM, investigation of downstream mixing kinetics of methane in nitrogen, and the comparison of 1D with 2D and 3D models.

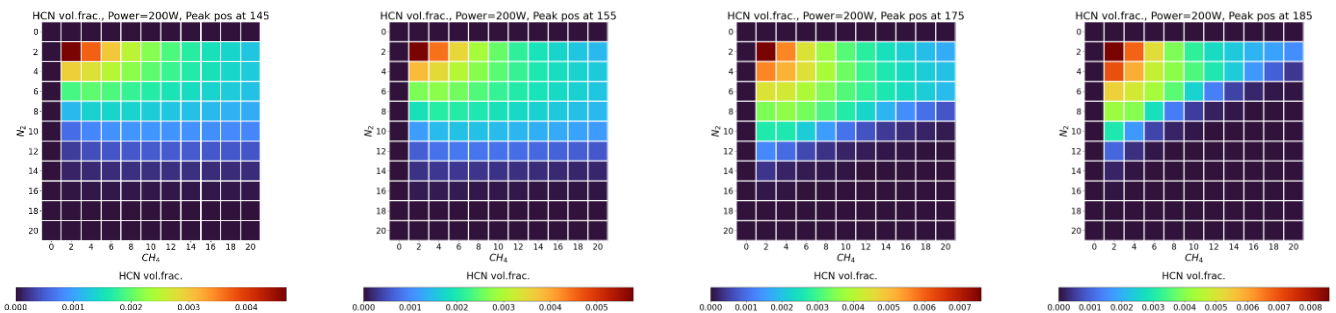
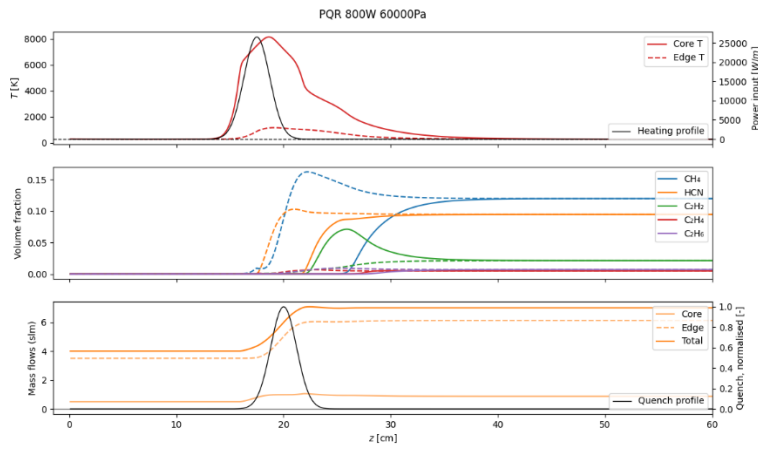
The CFD efforts have focused on modelling the geometry and reactor conditions of the microwave experiment at the lab scale. The nitrogen gas injection is modelled by an octagonal tangential gas injection, and the quench by a dual gas injection. To accurately model the experiment, oxygen gas was used for the plasma and a nitrogen quench was used. The CFD simulations model the temperature, flow, and species profiles in the reactor, which are compared to the measured values.



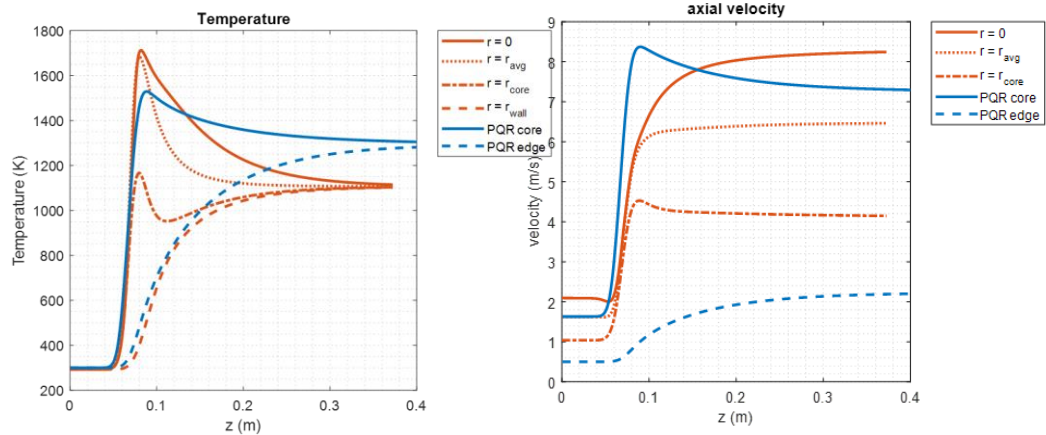
Close to the plasma, the radial temperature profiles match well with the experiment, while further downstream the modelling slightly overestimates the temperature. It is also apparent that some extra structures in the radial profile are not exhibited in the experimental data, because this data is time-averaged. This unsteady behavior is further analyzed in the CFD results by performing a dynamic mode decomposition. This decomposition yielded two dominant frequencies, one associated with the plasma fluctuations, and one with that of the quench region.

The downstream mixing of methane investigated the kinetics involved in the quench process under formation of HCN and C₂H₂. Heat is absorbed in the plasma core which increases the core temperature to 6000-8000K. Nitrogen radicals are formed in the core, but can only interact with CH₄ by mixing with the edge, where the methane is injected. As methane mixes with the core, it converts to HCN even before methane is mixed into the edge. Acetylene is briefly formed, but only in the core where the temperature is sufficiently high. The carbon yields are dominated by methane and HCN after reaction.

The production of HCN was investigated by scanning the input flow rate as well as the quench flow rate at otherwise constant reactor conditions. At smaller flow rates the HCN yields increases due to the higher specific energy input (since power is kept constant). The quench position is another important parameter; it was shown that the position of the quench should be close to the plasma but not too close to have the optimal effect.



axisymmetric model was compared with 1D modelling results. The axial temperature profiles are compared at various radial positions. Notably, the temperature profile at the core of the 1D model is very different from the 2D model. Future work will modify and upgrade the 1D models to improve the match between higher dimensional models.



Result 5: Definition and basic engineering of pilot plant including quench

Result 5	Pilot plant reactor design	Start M16	End M36
	Target group: Project team and stakeholders		
	Project goal: The pilot plant is necessary to gain insight into high volume plasma processing in an industrial environment		
	This result will provide the necessary input for the stakeholders/partners to decide on realization of the pilot plant.		
<i>A5.1</i>	<i>Activity 5.1: Pilot scale reactor design</i>		<i>IO</i>
	Lead: Sitech Partners: BCC/UM/TNO/Stamicarbon/Vitalfluid/Evonik	Start M16	End M36
D5.1	Indicator: Report Information obtained via indicator: Basic design and cost estimate (CAPEX + OPEX) of pilot scale system		Sitech M36
MP7	Pilot scale reactor design is completed		Sitech M36

Ebert HERA

A5.1

Ebert HERA is involved in engineering for the needed modifications in the Benchscale set-up to process HCN or NOx.

Based on this and the desired pilot plant scope we can start with the engineering process for a pilot plant. As basis for this pilot plant it would be a natural decision to base the design on the 500 kW Methane Pilot Plant to be built on Brightlands Chemelot campus.

This 500 kW Methane Pilot Plant is at this moment in the phase of Basic Engineering being ready.

In October 2025 we did organized a Front End Loading (FEL) session with all the stakeholders to define the goals for the pilot plant and to write a Business Need Memorandum (Project letter) to start in a correct way the engineering. This will be finalized in Q1 2026.

Result 6: Balancing energy demand

Result 6	Balancing the energy demand	Start M25	End M48
	Target group: Project team / stakeholders		
	Project goal: To get insights in the optimal conditions and operating parameters for mimimized operational cost		
	This result will provide a report of sensitivity analysis of the tons/day and MWh/ton on a model system		
A6.1	Activity 6.1: Energy optimization & heat integration		IO
	Lead: Sitech Partners: TNO/BASF SE/Evonik/Stamicarbon	Start M25	End M48
A6.2	Activity 6.2: Process optimization		IO
	Lead: Sitech Partners: TNO/BASF SE/Evonik/Stamicarbon	Start M31	End M48
D6.1	Indicator: Report Information obtained via indicator: Energy optimisation and heat integration of the pilot / demo scale reactor		Sitech M48
D6.2	Indicator: Report Information obtained via indicator: output of modelling study for optimized process		Sitech M48

A6.1+6.2:

No progress on these actions to report at this moment.

Result 7: System design towards a sustainable process

Result 7	System design towards a sustainable process	Start M25	End M48
	Target group: projectteam		
	Project goal: to get an understanding of the opportunities of plasma-based conversion on a systems level		
	This result will provide a report with optimized scenarios for system level integration that maximize the value of the entire chain		
A7.1	Activity 7.1: System integration NO _x		IO
	Lead: Sitech Partners: Vitalfluid/BASF SE/Evonik/UM/TNO/BCC/Stamicarbon	Start M25	End M48
A7.2	Activity 7.2: System integration HCN		IO
	Lead: Sitech Partners: Vitalfluid/BASF SE/Evonik/UM/TNO/BCC	Start M34	End M48

A7.1+7.2:

No progress on these actions to report at this moment.

Result 8: Conceptual design demonstration plant

Result 8	Business case analyse	Start M28	End M48
	Target group: projectteam/partners/stakeholders		
	Project goal: To determine the optimal design of a future demo plant		
	This result will provide a conceptual design of a demo plant based on input of experimental results and TCA/LCA analyses.		
A8.1	Activity 8.1: Definition of requirements demonstration plant		EO
	Lead: Sitech Partners: Vitalfluid/BASF SE/Evonik/Stamicarbon/TNO/BCC/UM	Start M28	End M36
A8.2	Activity 8.2: Preliminary study conceptual design and evaluation		EO
	Lead: Sitech Partners: Vitalfluid/BASF SE/Evonik/Stamicarbon/TNO/BCC/UM	Start M37	End M48
D8.1	Indicator: Report Information obtained via indicator: completed document with design requirements		Sitech M36
D8.2	Indicator: Report Information obtained via indicator: completed conceptual design		Sitech M48
MP10	Demonstration scale conceptual design is completed		Sitech M48

A8.1+8.2:

No progress on these actions to report at this moment.

Result 9: Safety and societal acceptance

Result 9	Safety and societal acceptance	Start M1	End M48
	Target group: public and private stakeholders; Society at large; project team		
	Project goal: Increase the societal acceptance of implementation		
	This result will, in addition to increasing societal acceptance, perform a sensitivity analysis of the business case for numerous technical and societal parameters.		
A9.1	Activity 9.1: Social impact study and LCA		EO
	Lead: Sitech Partners: Vitalfluid/TNO/Stamicarbon/UM/BCC	Start M1	End M24
A9.2	Activity 9.2: Infrastructural acceptance and preparation		EO
	Lead: Sitech Partners: Vitalfluid/TNO/Stamicarbon/UM/BCC	Start M37	End M48
A9.3	Activity 9.3: Safety aspects		EO
	Lead: Sitech Partners: Vitalfluid/TNO/Stamicarbon/UM/BCC	Start M7	End M39

The work on Result 9 did not start. According to the updated planning, the majority of the activities will take place in 2026.

Result 9.1

LCA execution is dependent on the Result 10. Deliverables from Result 10, such as process flow diagrams (PFD), mass and energy balances, will be used as an input data for LCA. LCA will be executed by PhD student from University Maastricht.

Screening (not full!) LCA will be performed, as the goal is to identify hot spots and obtain insights in the potential process improvements.

In addition, a starting point for Stakeholder analysis, Sustainability Development Goals (SDG) and Questions and answers (Q&A) will be prepared in parallel.

Result 9.2

Local integration study will start next year and should be developed in close collaboration with Result 7. It is also dependent on the Result 10, which is a base for processes that potentially will be integrated on the Chemelot site.

Result 9.3

Safety aspects will have to be aligned with the requirements of Brightlands Chemelot Campus (BCC):

- permits limitations for water, air and soil,
- supply of utilities, mostly electricity,
- plot/location selection and preparation,
- infrastructure,
- safety assessments and studies, etc.

For setups on the lab scale and APT20 setup, the discussions with BCC have started and approval of the safety check (the so-called A2 file) is expected before the setups become operational.

Result 10: Techno economic model study for business case analyses (benchmark green Haber Bosch + Ostwald)

Result 10	Techno economic model study for business case analyses	Start M1	End M48
	Target group: project team / stakeholders		
	Project goal: a techno-economic model of a pilot plant where a full cost-benefit analysis can be performed.		
	This result will provide a sensitivity analysis of the business case of plasma chemistry for alternative nitrogen-based feedstock such as NO _x with a low carbon footprint, performed on input data of technical and social nature.		
A10.1	Activity 10.1: Benchmarking using idealized values		IO
	Lead: TNO Partners: Sitech/Vitalfluid/BASF SE/Evonik/Stamicarbon/UM	Start M1	End M12
A10.2	Activity 10.2: Benchmarking using research reactor results		IO
	Lead: TNO Partners: Sitech/Vitalfluid/BASF SE/Evonik/Stamicarbon/UM	Start M13	End M36
A10.3	Activity 10.3: Techno-economic analysis		IO
	Lead: TNO Partners: Sitech/Vitalfluid/BASF SE/Evonik/Stamicarbon/UM	Start M37	End M48

The main goal of WP 10 is to create a techno-economic model (TEA) of plasma chemistry for alternative nitrogen-based feedstock with a low carbon footprint, where a full cost-benefit analysis can be performed.

In order to achieve this goal, a decision of which processes will be studied using nitrogen based plasma is required, producing at least a process flow diagram (PFD) and mass and energy balances (M&E balances) of such processes, as well as an understanding of the existing processes that will be substituted or, at least, used as a benchmark.

During 2025, progress was made on all of the previous points mentioned. It was defined that the plasma processes would look to substitute, or at least use as benchmark, the Ostwald process for HNO₃ production and the Andrussov process for HCN production. Aspen models for both of these processes have been produced, reviewed by partners, and accepted as

good basis for benchmarking the TEA. Process flow diagrams have been proposed for both the HNO₃ and the HCN plasma-assisted production processes, and shared with partners. The PFD for the HNO₃ process has been accepted. The PFD for HCN is under final discussion. Aspen models for both the plasma-assisted processes have been created based on the proposed PFDs to execute the M&E balances. The ASPEN model for HNO₃ has been sent to partners for review, and is under final discussion prior to approval. The ASPEN model for HCN is under review and final details prior to sharing with partners for discussion and approval.

All of the aforementioned work, sets the foundation for the actual execution of the TEA. Along with those requirements, the definition of the cases and scenarios to be studied is also a key part of the study. Cases to be studied have been proposed and accepted for the HNO₃ process, but not yet for the HCN process. The case studies include using experimental data in the approved models to generate a scenario to be studied that involves those results.

Once all preliminary work is completed, the actual TEA is expected to happen during 2026. Such a timeline has enough time for revisions, modifications and further additions required prior to the production of the final report in M48.