1 Project description

Name organisation	TNO
Name program	Sourcing of skids
Tender	European public sourcing program

Project name	CHARLIE: Hydrogenation setup & distillation setup
Project Number	231
Division	NETLAB

2 Project Introduction

Within the NETLAB venture, TNO intends to realise experimental test setups for the testing of different negative emission technologies, among others direct air capture and flue gas purification using novel solvents. One of the activities is based on CO_2 absorption and its subsequent use as a C1 building block to obtain value added chemicals (e.g. formic acid). Due to the high thermodynamic stability of CO_2, high energy compounds or electro-reductive operations are commonly required to transform CO_2 into other chemicals. Hydrogen is considered as an important high energy compound to realise this conversion.

The aim of the present project, named CHARLIE, is to develop and establish a hydrogenation setup and a stripper/distillation setup. Within the hydrogenation setup, a liquid is hydrogenated in a reactor equipped with a heterogeneous catalyst. The hydrogenated liquid is subsequently fed to a stripper/distillation setup where the feedstock is split into a light fraction and a heavy fraction. Because of the batch-wise operation of the hydrogenation step, the two units operate independently and are not interconnected in one single skid. The feed and products of each step will be respectively provided and stored using transportable vessels.

3 Project Background

The goal of TNO with the NETLAB is to demonstrate the feasibility of several negative emission technologies by constructing experimental skids in which these processes will be tested. These test installations can be used for complementary activities in carbon capture and utilisation (CCU) projects. The idea is that this installation becomes part of the open innovation facilities in which negative emission technologies can get accelerated towards higher technology readiness levels for a final industrial implementation to realise the climate goal of not exceeding the 1.5 °C threshold.

The four different technologies to be tested in the NETLAB are the following:

- Activity 1: Absorption;
- Activity 2: Adsorption test street;
- Activity 3: Carbon Capture and Utilisation, integrated CO_2 capture & conversion processes (i.e. CHARLIE process);
- Activity 4: Purification of the products.

The present tender deals with Activities 3 and 4, '*CCU*', more specifically, for the CHARLIE process and the subsequent purification of the products.

4 Scope and deliverables

The supplies/services will comprise basic engineering, detailed design, manufacture, transportation and installation of a setup capable of converting captured CO_2 into liquid C1 products in the hydrogenation reactor and concluding with the separation of the liquid products in the distillation column.

The setup shall primarily consist of:
- Hydrogenation reactor;
- Reactive distillation column;
- Miscellaneous units (e.g. pumps);
- All the necessary interconnected and self-contained skid units with individual connections to the site supplied utilities.

The tenderer must deliver a commercially available or customized hydrogenation reactor and a reactive distillation column, in accordance with the list of requirements.

4.1 Exclusions

The following will be excluded from the scope of supply:
- The catalyst to be used is out of the scope for the tenderer.

4.2 Scope, and content of the contract

The Contract (CHARLIE: Hydrogenation setup & distillation setup) relates to the provision of supplies, services or works as specified in the Programme of Requirements as applicable.

The key points are:

DESIGN:
- Basic engineering package of the demonstration unit;
- Detailed engineering for the demonstration unit.

PROCUREMENT & MANUFACTURE:
- Procurement and manufacture of equipment as per detailed design.

INSTALLATION:
- Installation of the components together (e.g. hardware, electrical, control) in a functional system – setup.

The setups SHALL be designed, constructed and installed as a mobile standalone setup. The setups will be located indoors.

INSPECTION and TESTING:
- Factory Acceptance Test (FAT) of the unit (e.g. leak test, mechanical integrity, test for performance and so forth).

TRANSPORTATION to TNO given address.
INSTALLATION at TNO given address:
- Site Acceptance Test (SAT) at the TNO given location in the Netherlands.

COMMISSIONING and DEMONSTRATION:
- Commissioning demonstration and training of the operators of the setup.

4.3 End result/deliverable

The result of the project is the commissioned and established demonstration units which will be in line with the programme of requirements. Next to the demonstration units, the supplier SHALL deliver the following documentation:

As part of the basic engineering package:

- Piping and Instrumentation diagrams;
- Layout drawings;
- Equipment specification sheets;
- Instruments specification sheets;
- Analysers specification sheets;
- Control narrative.

As part of detailed engineering, procurement and construction:

- As build documentation – P&ID, layout drawings, equipment drawings;
- Instruments data sheets;
- Analysers data sheets;
- Factory Acceptance Test and Site Acceptance Test – Validation Plan
- Operational manual;
- Maintenance manual.

All above described sets of documents of the basic and detailed engineering phase will be send to TNO for approval. After the approval of TNO, the next phase can start.

As part of safety assessment:

- HAZOP report (the HAZOP will be organized and facilitated by contractor and TNO will participate in the HAZOP sessions).

5 Functional description of the units

5.1 Hydrogenation reactor

Within this NETLAB tender, the first unit is a trickle bed hydrogenation reactor. Trickle-bed reactors are three-phase reactors in which gas and liquid reactants are generally contacted in a co-current down flow mode in the presence of heterogeneous catalysts and are used in a large number of industrial chemical processes (e.g. petroleum, petrochemical and chemical industries, pollutant abatement, biochemical and electrochemical processes). The majority of industrial trickle-bed reactors operate at high pressures, up to about 20-30 MPa in order to slow down catalyst deactivation, enhance the solubility of the gaseous reactant, achieve high conversion rates and attain better heat transfer.

5.1.1 Hydrogenation Process Description

The main reaction taking place in the trickle-bed reactor is a hydrogenation reaction. For this hydrogenation reaction the trickle bed reactor contains pellets of Pd catalyst on a carbon support.

The feed will be loaded to the reactor from a transportable storage tank using a dosing pump. After concluding the batch process, the products shall be collected in a transportable storage tank for downstream purification step utilizing a reactive distillation column, see section 5.2.

The trickle-bed reactor shall be operating in downflow co-current mode. The reactor shall consist of a jacketed packed-bed column made of stainless steel (or glass-lined compatible to handle corrosive materials) with the dimensions and operational conditions stated in Table 1. Pure hydrogen and a liquid mixture will be fed at the top of the reactor. Typically, this liquid mixture can be an aqueous solution of amines (including aqueous solution of ammonia) with ionic species such as bicarbonate and formate. The column shall be pressurized with hydrogen. The temperature in the reactor shall be controlled by thermostated water circulating in the jacket at a constant temperature. The temperature profile over the height of the reactor shall be monitored and logged by installing several temperature transmitters in the axial (vertical) direction of the reactor. The entire reactor should be insulated to minimize heat losses. In addition, the gas lines should be traced to avoid blocking of the lines as a consequence of gas expansion and to introduce the gas at the reactor temperature.

The liquid-gas mixture leaving the reactor will be sent to a separator from which the gas is either recirculated to the top of the reactor or vented through a back-pressure valve and diluted with N_2 to avoid creating an explosive mix of hydrogen with air. The liquid will be recirculated to the top of the reactor for the entire duration of the batch, to achieve high yield/conversion, using a pump (e.g. positive displacement dosing). To avoid pump damage and drying up of the reactor, level control should be installed at the sump and/or at the separator vessel.

A liquid redistributor on top of the bed shall be installed to ensure equal loading of liquid and gas at top of the catalyst bed. Moreover, void space shall be included to avoid direct impingement of the streams into the packed surface and allowing access to the top of the reactor.

For safety reasons, after depressurization of the reactor, the entire setup shall be flushed with N_2 to remove the H_2 content and leave the setup in a safe condition.
A schematic representation of the hydrogenation setup is presented in Figure 1: A process flow diagram of the trickle-bed reactor and the essential instrumentation. The gas return line within the red dashed box is optional, see requirement 6.2.2.5.. Effectively, the setup is a mobile standalone installation. Therefore, its design shall take into account the autonomous operation, regardless of installing interconnections meant to be used in the future for joining the upstream and downstream units to the hydrogenation reactor, namely Activity 1 and Activity 4. Moreover, the setup shall serve as a multipurpose testing unit and will be used beyond the NETLAB project. Hence, it shall be functional and adaptable to other processes and systems.

Typical process operating conditions, the trickle-bed dimensions and the catalyst properties are listed in Table 1. The list of requirements that the hydrogenation setup design shall comply with can be found in sections 6.2 and 6.3.

Table 1: Reactor dimensions, typical operating conditions, catalyst properties and construction material of the hydrogenation step

Reactor dimensions		***Operating conditions***	
Total length (m)	0.5	Liquid flow rate (L/h)	28.5
Diameter (m)	0.05	Gas flow rate (L/h)	50
Active catalyst length (m)		Pressure (bara)	1 - 100
Sump height (m)		Temperature (°C)	20 - 80
Catalyst properties		Cycle/batch time (h)	4
Pellets dimensions (mm)	3		
		Construction material	
		Lined materials that can withstand low pH values	2

5.1.2 Catalyst Load

The catalyst bed shall be supported to avoid displacement of the catalyst particles resulting in maldistribution of the particles over the bed. In addition, catalyst separation screens with adequate mesh size shall be installed between the catalyst and the (inert) support. The screens on top of the bed keep the ballast (e.g. ceramic balls that protect the catalyst bed from direct impingement of the inlet feedstock stream) out of the bed. In addition, fine screens, whose openings are less than the catalyst size, shall be installed at the bottom of the catalyst bed to prevent catalyst pieces and fines generated during normal operation from reaching the outlet and should be designed to have a maximum open surface area to avoid increase in the total reactor pressure drop.

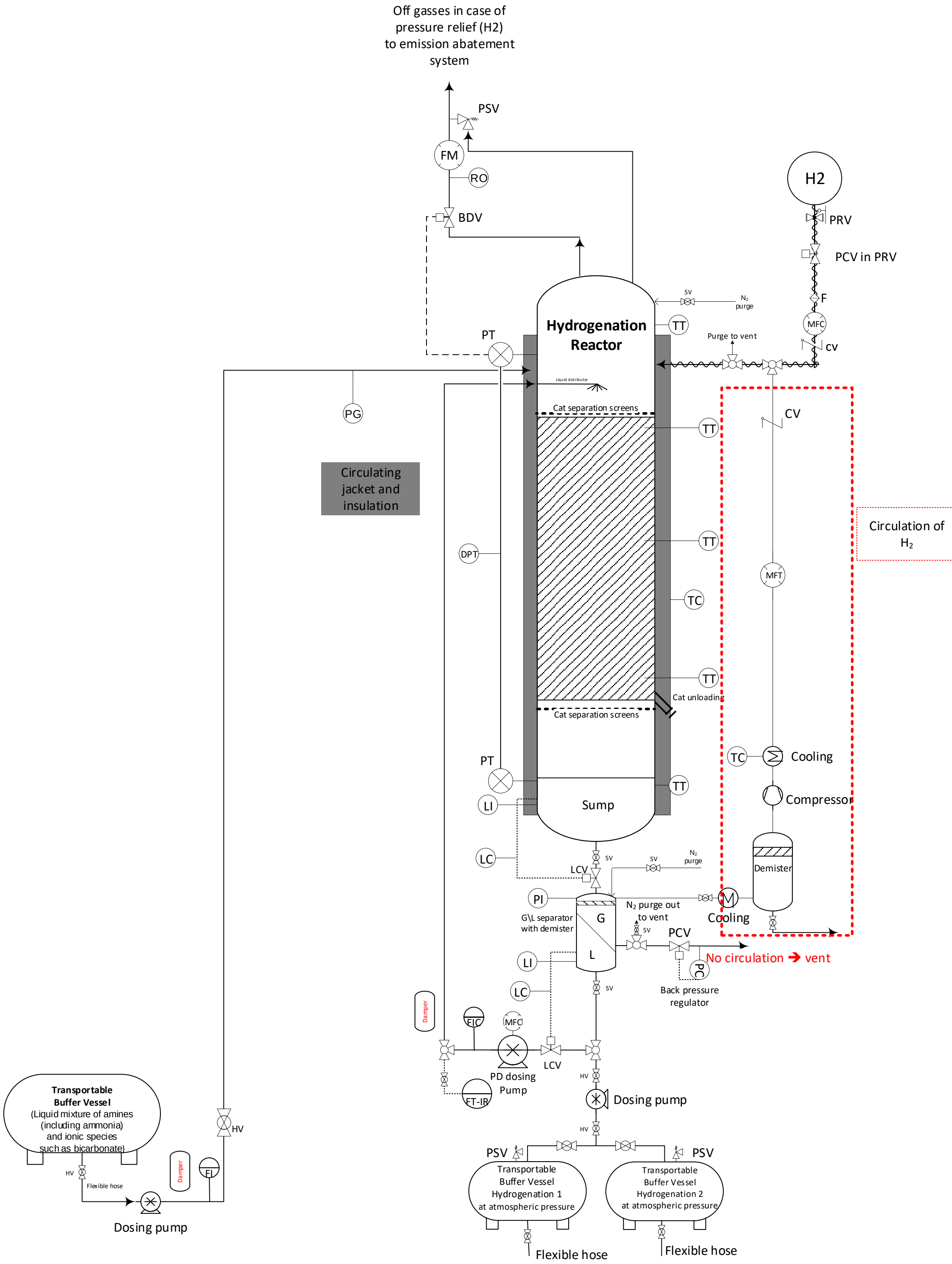

Figure 1: A process flow diagram of the trickle-bed reactor and the essential instrumentation. The gas return line within the red dashed box is optional, see requirement 6.2.2.5.

5.2 Reactive Distillation Setup

5.2.1 Reactive Distillation Process Description

The liquid feedstock shall be pumped and heated before entering the column. The top fraction leaving the column shall pass through a partial condenser. The gas fraction from the gas-liquid separator shall be sent to a scrubber. The liquid fraction shall be sent back to the top of the column as reflux and/or sent to a product collection vessel (e.g. for analysis and yield calculations) with a predefined reflux ratio. To avoid drying up of the sump, a level controller should be installed. Moreover, the reboiler should provide sufficient energy (e.g. jacketed oil circulating or electrical jacket around the sump). To operate under vacuum conditions the gas compartment of the gas-liquid separator should be connected either directly to the inlet of a vacuum pump or via the scrubber. The temperature profile over the height of the column shall be monitored and logged by installing various temperature transmitters in the axial (vertical) direction of the reactor. The column should be insulated to minimize heat losses. A process flow diagram of the reactive distillation setup is shown in Figure 2. Effectively, the setup is a mobile standalone installation. Therefore, its design shall take into account the autonomous operation, regardless of installing interconnections meant to be used in the future for joining to the upstream units.

The column and its internals (e.g. packing materials) should withstand the operational conditions and the acidic environment. Therefore, we suggest to use lined construction materials or steel containing high concentrations of molybdenum.

The column should be designed to be flexible in its functionality and operability. Therefore, it should fulfil the following requirements:

- Multiple inlets: bottom, middle and top;
- Modular internals: packing and liquid redistributors;
- Applicable beyond CHARLIE separation split;
- Used in vacuum distillation for high boilers.

The process operating conditions and the column dimensions are listed in Table 2. The list of requirements that the reactive distillation setup design shall comply with are listed in sections 6.4 and 6.5.

Table 2: Column dimensions, operating conditions and construction material of the distillation step

Reactor dimensions		***Operating conditions***	
Total length (m)	1.5	Liquid flow rate (L/h)	2.5
Diameter (m)	0.02	Pressure (bara)	Vac - 8
Packing height (m)	1	Temperature (°C)	50- 180
Sump height (m)	0.3	Formic acid concentration (M)	
Void space (m)	0.2	***Construction material***	
		Lined materials that can withstand low pH values	2

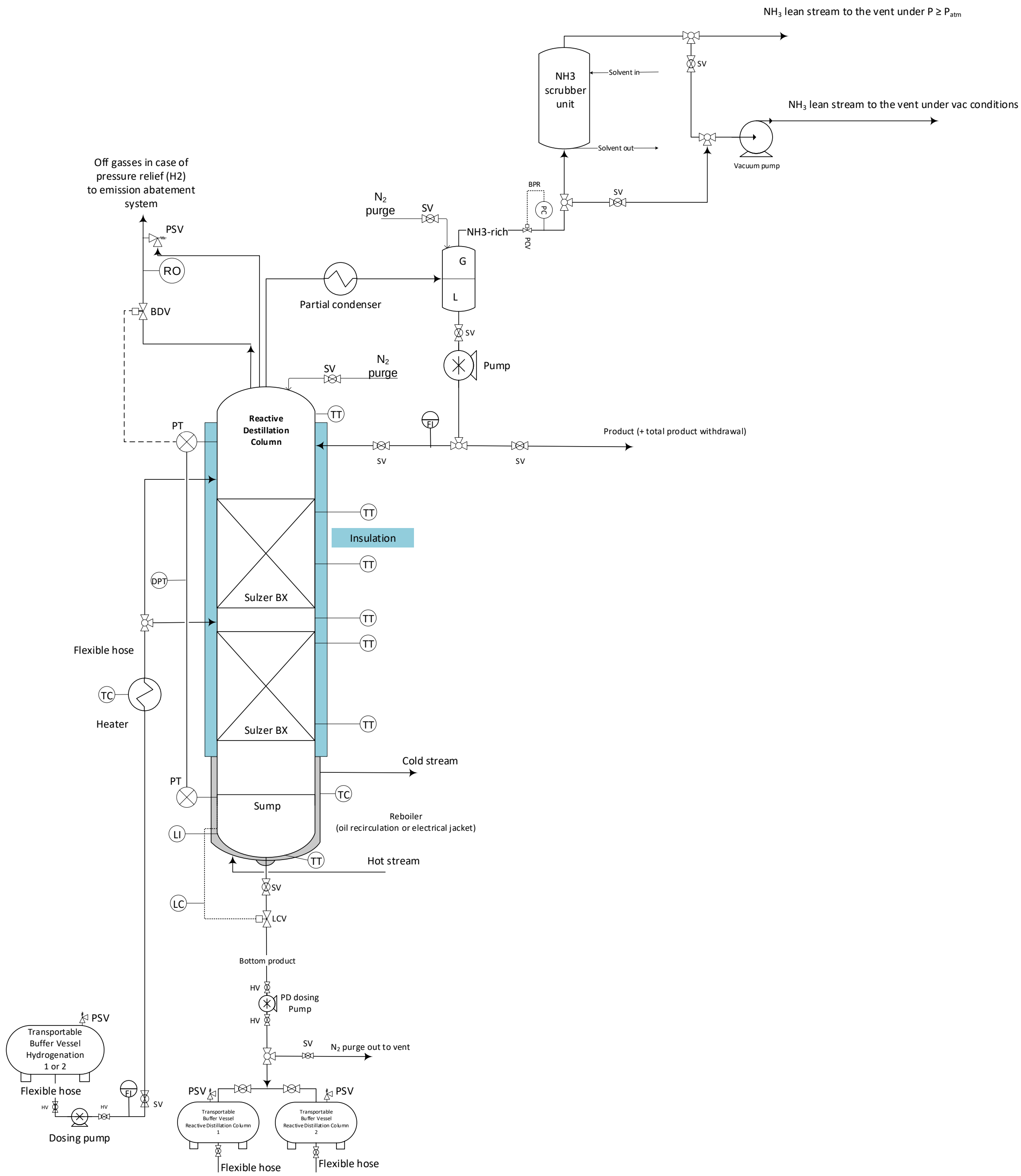

Figure 2: A process flow diagram of the reactive distillation column and the essential instrumentation.

6 Programme of requirements

The Programme of Requirement is divided into the following sections:

- Delivered goods and regulations
- Organizational aspects: Procedure, Planning, Risk and Risk Mitigations (section 6.1).
- Technical functional aspects for the Hydrogenation Reactor setup (sections 6.2 and 6.3).
- Technical functional aspects for the Reactive Distillation Column setup (sections 6.4 and 6.5).

The delivered goods need to comply with the following regulations:

Nr.	General regulations requirements
6.1.1	The units SHALL comply with all applicable Dutch laws, regulations, rules, standards and guidelines. Furthermore, it shall also comply with European standards and requirements, in particular risk management and safety regulations.
6.1.2	The delivered goods SHALL have CE conformity.
6.1.3	The design of the units SHALL be in line with international engineering standards.
6.1.4	Any Party (i.e. entity, governmental body or individuals) that responds to this tender, WILL be screened according to the TNO Sanctions & Export Control Policy. In case of conflicts arising from this, TNO has the right to decline the response of the Party upon its own discretion, with no further liabilities towards Party.
6.1.5	The transportable buffer storage tanks SHALL be coupled with quick connectors.
6.1.6	Tubing at the process side SHALL be fractional sized seamless stainless steel tubing conform Swagelok specifications.
6.1.7	Tube connections SHALL be fractional sized stainless steel Swagelok twin ferrule connectors.
6.1.8	Flowmeters and controllers SHALL be Bronkhorst with FLOWBUS data connection.
6.1.9	It is highly preferred to have as control interface environment the software LabVIEW, as it is the current standard at the TNO premises.
6.1.10	Frames of the setups SHALL be item systems “line 10”.

6.1 Project plan and implementation

The object of the present tender can be seen as two main stages:

- The design phase:
    - In the design phase, it is envisaged that it will involve a team of engineers from both TNO as well as the tenderer.
- The building and commissioning phase.

Nr.	Planning & implementation requirements
6.1.1.1	Language for all documentation and correspondence SHALL be in English.
6.1.1.2	The official language within the TNO team SHALL be English. The team members are expected to be sufficiently proficient in both written and verbal language.
6.1.1.3	With the external key team members (i.e. staff from tenderer), on a personal level, a Non-Disclosure Agreement SHALL be signed.

6.1.1.4	The complete installation (Hydrogenation reactor setup + Reactive distillation column setup) SHALL be ready BEFORE August 21 2021.
6.1.1.5	The overall plan for the manufacturing and delivery of the installation (Hydrogenation Reactor setup + Reactive Distillation Column setup) SHALL consist of the design phase, and the building and commissioning phase.
6.1.1.6	The design phase will consist of the following tasks: - T1. Requirement specification; - T2. Hydrogenation reactor + Reactive distillation column design; - T3. Hydrogenation reactor + Reactive distillation column setups conceptual design; - T4. Hydrogenation reactor + Reactive distillation column setup engineering design; - T5. Hydrogenation reactor + Reactive distillation column components specification; - T6. Safety study. Tenderer SHALL accept that TNO will review all documents and deliverables out of the design phase, so it should be possible to make recommendations and changes during the design phase.
6.1.1.7	The building and commissioning phase will consist of the following tasks: - T7. Choice of suppliers and ordering of components; - T8. Mechanical and electrical assembling, construction and manufacturing; - T9. Automation system; - T10. Commissioning: FAT and SAT; - T11. Final documentation; - T12. Training of TNO personnel. The building and commissioning phase will start only if all documents, outputs and deliverables from the design phase produced by the tenderer have been approved by TNO. Tenderer SHALL accept that TNO will review all documents and deliverables out of the building and commissioning phase, so it should be possible to make recommendations and changes during this phase.
6.1.1.8	Task 1, '*Requirement specification'*, is led by TNO and the requirements SHALL be formulated together with the tenderer.
6.1.1.9	Task 2, '*Hydrogenation reactor + Reactive distillation column design'*, is carried out by the tenderer. All possible IP generated with the design of the setups WILL remain property of TNO.
6.1.1.10	In Task 2, '*Hydrogenation reactor + Reactive distillation column design'*, in case of a third party company that takes care of the design, the tenderer SHALL involve this third party company in the discussions with TNO for the design of the two setups. As well, all IP generated with the design of the two setups still remains property of TNO, regardless the involvement of a third party.
6.1.1.11	Task 3, '*Hydrogenation reactor + Reactive distillation column setups conceptual design'*, is responsibility of the tenderer, and it results into a conceptual design which can be a process flow diagram. TNO should be consulted and should approve this diagram before the next phase begins. The completion of this task should take into account the requirements defined at Task 1 and the one agreed upon at the signing of the contract.
6.1.1.12	Task 4, '*Hydrogenation reactor + Reactive distillation column setups engineering design*', is responsibility of the tenderer, and it should have as output the engineering

	design of both setups based on input from Task 1 and Task 3 and it should be approved by the TNO engineering team. This task has two outputs: - Output 4.1: the P&ID of the Hydrogenation reactor + Reactive distillation column setups; - Output 4.2: the Design document.
6.1.1.13	Task 5, '*Hydrogenation reactor + Reactive distillation column components specification*', is responsibility of the tenderer, and it results into a component specification and a list of components. For the completion of this task, the input from previous tasks should be taken into account. This list should be as concrete as possible and supplying companies already need to be indicated here.
6.1.1.14	Task 6, '*Safety study*', is responsibility of the tenderer but TNO will be part of the safety discussions. The tenderer is responsible to compile and deliver the safety documentation of the installation and process (HAZOP methodology to be used here).
6.1.1.15	The design phase SHALL not take more than 6 months from beginning of Task 1 till the completion of Task 6.
6.1.1.16	Task 7, '*Choice of suppliers and ordering of components'*, is responsibility of the tenderer, and consists of the ordering of the components. A list of all the components and the technical documentation of the main components will be prepared by the tenderer to be delivered to TNO.
6.1.1.17	Task 8, '*Mechanical and electrical assembling, construction and manufacturing*', is responsibility of the tenderer, and consists of the assembling and building of the Hydrogenation reactor + Reactive distillation column setups, as well as the manufacturing of both setups. A setup layout diagram and a detailed drawing of the two setups will be provided to TNO by the tenderer. Effectively, the setups are mobile standalone installations on wheels and placed in drip trays.
6.1.1.18	Task 9, '*Automation system*', is responsibility of the tenderer, and consists of the creation of the automation system for the Hydrogenation reactor + Reactive distillation column setups, as well as their implementation in separately constructed setups, incl. alarms, wiring, cabinet installation, etc. A manual of control system will be provided together with the software. LabVIEW is preferred software.
6.1.1.19	Task 10, '*Commissioning: FAT and SAT*', is responsibility of the tenderer, and consists of the Factory Acceptance Test (FAT) at the tenderer premises, and the Site Acceptance Test (SAT) at the chosen TNO premises. The two deliverables of this task are the commissioning report for the FAT, and the report for the SAT.
6.1.1.20	The FAT and SAT SHALL comply with a list of requirements, stated in a validation plan, proposed by the supplier, and agreed by TNO. This validation plan SHALL be finalised two months before the start of the FAT and SHALL be approved by TNO.
6.1.1.21	Task 11, '*Final documentation*', is responsibility of the tenderer, and consists of the preparation of all necessary documentation: technical operation manual, declaration of conformity.
6.1.1.22	Task 12, '*Training of TNO personnel'*, is responsibility of the tenderer, and SHALL consist of: - the use (covering at least start-up of the apparatus, usage of the software, setting up and performing calibration tasks, setting up and performing an experiment, evaluating data measurements and reporting); - maintenance of the pilot setups by TNO personnel. The training SHALL take place at the location where the setups are placed.
6.1.1.23	The building and commissioning phase SHALL not take more than 6 months from beginning of task T7 till the completion of task T12.

6.1.1.24	After the completion of Task 12, the delivered installation SHALL have a test period of 2 months, in which the delivered installation must comply with the agreed specifications and without faults or malfunctions.

The requirements related to the FAT and SAT can be found in the following tables:

Nr.	Factory Acceptance Test (FAT) and Site Acceptance Test (SAT)
6.1.2.1	A Factory Acceptance Test (FAT) SHALL be performed at the factory before delivery to TNO. TNO will observe the FAT testing and take notes for recommended improvements before delivery of the setups.
6.1.2.2	A Site Acceptance Test (SAT) SHALL be performed at TNO after delivery. Following a successful SAT, TNO will test the setups during a test period.
6.1.2.3	The requirements SHALL be validated according to a validation plan proposed by the supplier and agreed by TNO.
6.1.2.4	A first draft of this validation plan SHALL be supplied to TNO before the delivery of the design phase.
6.1.2.5	The validation plan SHALL be finalized two months before the start of the FAT and SHALL be approved by TNO.
6.1.2.6	The validation plan will be used in both the FAT and the SAT.

Nr.	The SAT contains the following checkpoints:
6.1.3.1	The system will be checked for damages.
6.1.3.2	The proper functioning of the equipment will be checked: • Mechanical functions; • Electrical safety- and switching functions; • User interface(s), including software.
6.1.3.3	All requirements and possible preferences will be checked; the presence and quality of the documentation will be checked.
6.1.3.4	A full acceptance test on-site must be performed by the tenderer in cooperation with and in the presence of TNO. The tenderer SHALL put forward a FAT and SAT validation plan. The details of the FAT and SAT SHALL be agreed between TNO and the tenderer. Following the approved SAT, the delivered equipment SHALL be at the unrestricted disposal of TNO for a test period of two months. If the system works according to the agreed specifications and without faults or malfunctions during this period, the test period is approved. If not, the faults or malfunctions shall be amended and another test period of two months should successfully be completed and approved.

Nr.	Validation plan for FAT & SAT
6.1.4.1	The connection of the components that might trigger a warning and/or alarm to the central control system will be checked for errors and connectivity issues.
6.1.4.2	The safety components, (e.g.: pressure relief valves, flammable gas sensor, etc.) will be set up and inspected.
6.1.4.3	The different components of the setup will be inspected to check whether the lay-out of the as-built setup is in correspondence with the delivered documentation & P&ID.
6.1.4.4	The setup will be checked for leakages in a control experiment with water.
6.1.4.5	The setup will be checked in a simulated experiment at relevant process conditions to test all safety and instrumentation equipment, as well as the correct functionality of all sub-systems.
6.1.4.6	The transfer mechanism for the contents of the vessels (feedstock vessel transfer to reactor/column vessel, and from the latter to the production vessels) will be inspected to check any leakages or other unexpected flaws.

6.1.4.7	The response of the setup will be checked in a simulated crash of the control system.
6.1.4.8	The emergency shutdown and power cut procedures will be tested to check whether they trigger the actions reported in the safety documentation.
6.1.4.9	The emergency shutdown button will be tested.
6.1.4.10	The setup will be cautiously examined to evaluate the robustness and flexibility to switch between the different functionalities and for the uncomplicated exchange internals. The setup must ensure no leaks and be gas tight.

Nr.	**Failure in FAT / SAT**
6.1.5.1	In the event that the Deliverables fail to meet the Acceptance Criteria for the FAT and the SAT, as the case may be, the parties SHALL jointly set out such failures in a written statement, to be signed by both parties.
6.1.5.2	On TNO-side this will be done by the TNO project manager and the dedicated project team. Tenderer SHALL provide the TNO project manager with a corrective action plan for such failures within fifteen (15) business days (or different period agreed to by the Parties) of the date of signing of such statement and, upon approval of such corrective action plan, tenderer SHALL correct such failures at no additional charge within the timeframe laid down in the corrective action plan.

The requirements related to the Engineering Change Notice (ECN) can be found in the following table:

Nr.	**Engineering Change Notice (ECN) after contract award**
6.1.6.1	All Engineering Change Notice and acceptance or rejection of such notices shall be in writing and made pursuant to the ECN procedure set forth below. All changes made by TNO or contractor are subject to mutual agreement of the parties. When the change affects pricing about the delivered setup, the written approval must be in the form of a purchase order issued by TNO. When the change affects specifications about the delivered setup, the written approval must be issued by TNO.
6.1.6.2	Upon TNO's submission of an ECN, Supplier will as soon as reasonably possible advice TNO of the resulting impact on cost, Time Schedule and performance changes if applicable and will provide such information as TNO may reasonably request to determine the reasonableness of the cost and delivery schedule impact. The parties will negotiate the ECN request in good faith, including reasonable adjustment of cost, schedule and/or other Project and Agreement terms. After reaching agreement on such cost, schedule and other terms, Supplier will proceed with the ECN.
6.1.6.3	Supplier may request an ECN, provided cost and delivery impact are properly detailed with such information as will permit TNO to determine the reasonableness thereof. The parties will negotiate the ECN request in good faith, including reasonable adjustment of cost, schedule and/or other Project and Agreement terms. After reaching agreement on such cost, schedule and other terms, Supplier will proceed with the change notice.

The tenderer is required to provide an answer for the following preference:

Nr.	**KW1 Project plan and implementation**
KW1	TNO wants a proposal in the form of a project plan, including a planning, risks (on the side of the tenderer) and necessary mitigation actions. This project plan should have a clear link to this project and take into account the requirements as described. The project plan should describe how this is best achieved, and that the specified delivery time is met. The proposed tasks by TNO in the design and building and commissioning phases shall be present in the proposed project plan by the tenderer. The tenderer is free to suggest modifications and/or additions to the proposed tasks by TNO. If tenderer wishes to suggest changes to the workflow, TNO expects clear reasoning behind this.

	Please include the following items in the project plan: - Planning; - Risks and Risk mitigation actions, describing the 5 most important risks for realisation of the project by the tenderer in terms of cost and time, together with mitigation measures proposed; - Milestones; - Meetings (when and where), minutes & change notifications; - Deliverables & documents; - Listing of estimated total hours and/or budget of TNO/Tenderer per stage; - Design, procurement (purchase of components), project management, building & commissioning; - Preliminary plan for a maintenance service of the delivered goods (e.g.: for non-Dutch tenderers, maintenance tasks can be outsourced to a local company to avoid long waiting periods for the tenderer to travel to the TNO premises); - Brief description of the team that will work on the project, with the title and the function they will perform (3 lines per person).
	The entire answer should be concise and easily readable. The entire answer should be no more than 20 (twenty) A4 pages. If the answer exceeds twenty A4 pages, the additional pages will be disregarded.

6.2 Hydrogenation reactor setup technical design

In the following tables, the requirements and preferences for the hydrogenation reactor setup are presented.

Nr.	Hydrogenation Reactor Requirements
6.2.1.1	The reactor SHALL have a total height of 50 cm and an inner diameter of 5 cm. The catalyst fixed-bed SHALL have a total height of 40 cm. The void space and the sump will have equal height of 5 cm each.
6.2.1.2	The reactor SHALL be able to circulate either only liquid or both liquid and gas streams leaving the reactor for four hours. The base case circulation rates are: - Liquid: 28.5 L/h - Gas: 50 nL/h (n=normal). Having the freedom to vary the fluid flow rates enables the researchers to investigate the limiting cases of the flow regimes and the catalyst wetting efficiency.
6.2.1.3	A liquid distributor SHALL be installed above the top of the catalyst bed to minimize the entrance effects.
6.2.1.4	The reactor SHALL include flanges at the top and bottom to enable dismantling for cleaning purposes and discharging the catalyst for regeneration and/or replacement.
6.2.1.5	The reactor SHALL be gas tight and leak free.
6.2.1.6	The reactor SHALL be insulated to avoid heat losses.

Nr.	Hydrogenation Reactor Design Requirements
6.2.2.1	The reactor SHALL consist out of three (main) compartments: - The void spaces at the top; - Supported catalyst bed; - The sump.
6.2.2.2	The pressure drop over the reactor SHALL be measured using pressure gauges and a differential pressure transmitter.

6.2.2.3	The temperature profile over the reactor SHALL be measured using AT LEAST 5 temperature transmitters
6.2.2.4	The reactor temperature SHALL be controlled by thermostated water/oil circulating in the jacket.
6.2.2.5	The effluent from the sump SHALL enter a gas-liquid separator equipped with a demister. The liquid will in all cases be recycled and for the gas phase there are two options to be investigated during the design: - Recirculation of the gas from the gas-liquid separator after compression and cooling to the top of the reactor; - Venting the gas via a back-pressure regulator and diluting with N_2.
6.2.2.6	The liquid stream returning to the reactor SHALL have a sample tap equipped with a needle valve to extract liquid for analysis using FT-IR, and SHALL be inherently safe.

Nr.	Hydrogenation Reactor General User Requirements
6.2.3.1	The reactor SHALL be able to operate at temperatures between 20 and 80° C.
6.2.3.2	The reactor SHALL be able to operate at pressures from atmospheric to 100 bara.
6.2.3.3	The reactor SHALL be able to operate at liquid flowrates 10 – 40 L/h.
6.2.3.4	The reactor SHALL be able to operate at gas flowrates 10 – 70 nL/h. (n=normal).
6.2.3.5	The reactor and all wetted parts SHALL be resistant to low pH values, AT LEAST 2-4.
6.2.3.6	The reactor SHALL have a lifetime of AT LEAST 5 years of 24/7 continuous operation, with respect to corrosion resistance, mechanical stability, etc.
6.2.3.7	The reactor SHALL be robust and functional to allow to be multiple times easily assembled and disassembled by the operator.
6.2.3.8	The reactor SHALL have spare parts of critical components (e.g.: fittings for liquid inlet & outlets etc.).
6.2.3.9	The sump of the reactor SHALL have a level indicator and a level controller.
6.2.3.10	The gas-liquid separator SHALL have a level indicator and a level controller.
6.2.3.11	Pressure safety valve SHALL be installed at the top of the reactor.
6.2.3.12	A blow down valve in combination with a restricted orifice and a flow meter SHALL be installed at the top of the reactor to allow safe release of the gas phase.

6.3 Hydrogenation setup technical design

In the following tables, the requirements and preferences for the setup around the hydrogenation reactor are presented.

Nr.	Hydrogenation Reactor Setup Requirements
6.3.1.1	The hydrogenation reactor setup SHALL consist of the following **sections**: 0. Utilities; 1. Liquid feedstock line to the reactor; 2. Liquid recirculation line from the effluent of the reactor to the top; 3. Gas feedstock lines; 4. Gas recirculation line from the effluent of the reactor to the top; 5. Gas-liquid separator; 6. Water bath; 7. Product discharge.
6.3.1.2	Section 0. Utilities of the hydrogenation reactor setup SHALL feature a sensor, to be placed inside the setup to detect any possible H_2 (or any flammable compound) in the atmosphere inside the space of the setup, and must be connected to an alarm system.
6.3.1.3	Section 1. Liquid feedstock charge to the reactor SHALL contain a transportable buffer storage, a pump (e.g. dosing pump) to allow feeding the reactor and a liquid flow meter.

6.3.1.4	Section 2. The liquid recirculation line SHALL contain a dosing pump to allow recirculation of the liquid effluent of the gas-liquid separator to the top of the reactor. In addition, a liquid flow meter/indicator should be installed in the discharge side of the pump. Moreover, the liquid stream returning to the reactor SHALL have a sample tap equipped with a needle valve to extract liquid for analysis using FT-IR.
6.3.1.5	Section 3. Gas lines of hydrogen to the hydrogenation setup SHALL contain: - Pressure relief valve; - Pressure control calve; - In-line filter; - Mass flow controller; - Check valve; - A three-way valve to combine with the gas recirculation line; - A three-way valve to purge the gas to vent after depressurising the reactor and venting using N_2 to avoid any hazardous situation caused by H_2 accumulation in the reactor and the lines. - Tracing to avoid blocking of the lines due to cooling effect of gas expansion.
6.3.1.6	Section 4. The gas recirculation line SHALL contain a water-cooled heat exchanger before the demister which removes condensates followed by a compressor to bring the gas to the appropriate pressure and a controlled cooler to remove the compression heat. In addition, a mass flow transmitter and a check valve SHALL be installed.
6.3.1.7	Section 5. The gas-liquid separator SHALL be equipped with a controlled N_2 purge mechanism to flush the lines and the reactor.
6.3.1.8	Section 6. The temperature in the reactor SHALL be controlled by thermostated water circulating in the jacket at nearly a constant temperature. The circulating water bath of the setup SHALL have a cooling capacity of AT LEAST 1 kW, with a minimal temperature of 20° C.
6.3.1.9	The Section 7. The product discharge of the hydrogenation reactor setup SHALL contain two buffer storage vessels with a storage capacity of AT LEAST twice the content of the reactor, and a pump to transfer the contents of the reactor to an external setup or container. The buffer vessels SHALL be equipped with pressure safety valves to release any H_2 gas build-up in the vessels.

Nr.	Hydrogenation Reactor Setup & Control System Requirements
6.3.2.1	The hydrogenation reactor setup SHALL be assembled in a frame with lockable wheels that allows the setup to be movable. This means that it can be easily disconnected and reconnected for transport through laboratory doors. In addition, adjustable feet should be placed for stable final placement during operation. The whole setup will be contained by the frame when disconnected.
6.3.2.2	When operating the reactor setup, it SHALL not exceed a noise limit of 80 dB.
6.3.2.3	The reactor setup SHALL contain computer accessories in which the control software is installed and operative. The computer SHALL be integrated in reactor setup.
6.3.2.4	The operator SHALL be able to easily reach the instruments and sample points in the setup manually for maintenance and modification purposes.
6.3.2.5	Sufficient lighting SHALL be mounted in the setup to facilitate operation.
6.3.2.6	The reactor setup SHALL include a control system to operate the setup, incl. hardware and software.
6.3.2.7	The reactor setup SHALL be fully automated, i.e., it shall be able to record data from sensors autonomously, and run unattended without the action of an operator (continuous operation).
6.3.2.8	The reactor setup SHALL be able to be operated remotely through an internet connection.
6.3.2.9	The reactor setup SHALL have a data-logging system for all the sensors of the setup to record all variables measured during operation.
6.3.2.10	The reactor setup SHALL record all available raw data from the installed sensors.

6.3.2.11	The reactor setup SHALL record all data on a hard disk, so that, in case of a power failure, the loss of data shall be of maximum 1 minute.
6.3.2.12	The reactor setup SHALL have spare parts available for AT LEAST 1 year after delivery and SAT.
6.3.2.13	The reactor setup SHALL be operated by TNO personnel at the chosen premises in which the setup will be delivered and installed.
6.3.2.14	The reactor setup SHALL be operated according to the TNO regulations of the chosen premises.
6.3.2.15	The reactor setup SHALL feature buttons for emergency stop of the operation that are easily reachable by the operators.
6.3.2.16	The reactor setup SHALL feature pressure relief valves or a similar system to prevent a dangerous overpressure in any part of the system.
6.3.2.17	The reactor setup SHALL feature leak trays or drip trays to allow the collection of any possible spilled liquid or substance from the setup.
6.3.2.18	All piping and tubing in the reactor setup SHALL be easily exchangeable. When applicable, for stainless steel piping, it is highly preferred to have Swagelok Imperial tubing in the reactor setup, as it is the current standard at the TNO premises.
6.3.2.19	The reactor setup SHALL feature a status light that is easily visible, with three different colours: - Green light: normal operation; - Orange light: setup in operation and off the setpoints (e.g. over-pressure, over-temperature); - Red light: critical alarm indicating failure conditions (e.g. leaks, reactor malfunctioning). The lights of the status lights do NOT blink or flash, i.e., are continuously on or off. In addition, a buzzer in the range of 70-100dB will be added to alert operators when the setup is operating at failure conditions.
6.3.2.20	The reactor setup SHALL alert the operators in case of an alarm with a sound and lighting system.
6.3.2.21	The control system of the reactor setup SHALL allow the definition of different situations, like Emergency Shutdown, or Power cut, that are triggered by specific alarms, and prompt actions in the system to safely stop the setup operation.
6.3.2.22	All error codes, alarm situations and warnings SHALL be recorded and logged into the system.
6.3.2.23	The control software interface SHALL be open source for the TNO personnel to have access and be able to modify it. It is highly preferred to have as control interface environment the software LabVIEW, as it is the current standard at the TNO premises.

The tenderer is required to provide an answer for the following preference:

Nr.	KW2 Hydrogenation Reactor Setup Technical Design
KW2	The proposed PFD for the reactor setup (chapter 8 Appendix) is an initial suggestion to start with the design of the installation. Given the programme of requirements for the reactor setup, especially those referred to Sections 3 & 4, *'Gas feedstock lines' & 'Gas recirculation line from the effluent of the reactor to the top'*, it is expected from the tenderer to provide a basic preliminary conceptual design for the reactor setup, complying with the mentioned

	list of technical requirements, that comprises the 7 abovementioned sections of the reactor setup. The tenderer must provide the following: • a basic conceptual design of the reactor setup; • a basic preliminary PFD for the reactor setup; • information about components and parts that will be in contact with the liquid mixture (e.g.: pipelines, valves, T-pieces, vessels, sensors, pumps, etc.); • a list of components with spare units that are necessary for the setup; The key highlights of the design must be presented, along with the main advantages and characteristics. Address the challenges and solutions in the design, and the motivation to any proposed modifications to the presented PFD for the reactor setup (chapter 8 Appendix Appendix). Provide information about the reasons to choose the selected components. Please be aware that it is not the intention to have a detailed and complete engineering design, but just the main guidelines and the strategy to follow during the design phase to come up with a successful setup.
	The entire answer should be concise, easily readable and not too extensive. Preliminary sketches and diagrams can also be part of the answer.

6.4 Reactive distillation column setup technical design

In the following tables, the requirements and preferences for the reactive distillation column setup are presented.

Nr.	Reactive Distillation Column Requirements
6.4.1.1	The distillation column SHALL have a total height of 150 cm and an inner diameter of 2 cm. The distillation column SHALL have packing units with a total height of 100 cm. The distillation column should be designed to be flexible in its functionality and operability. Therefore, it should fulfil the following requirements: - Multiple inlets: bottom, middle and top; - Modular internals: packing and liquid redistributors; - Applicable beyond CHARLIE separation split; - Used in vacuum distillation for high boilers. The void space will have a height of 20 cm and the sump will have height of 30 cm.
6.4.1.2	The distillation column top stream SHALL be fed to a partial condenser. Part of the condensed fraction SHALL return to the column as reflux and part will be extracted as product. The reflux ratio SHALL be controlled. Having the freedom to vary the fluid flow rates enables the researchers to investigate the limiting cases of the flow regimes and the separation efficiency.
6.4.1.3	A liquid distributor SHALL be installed above the top of the packing bed to minimize the entrance effects.

6.4.1.4	The distillation column SHALL include flanges at the top and bottom to enable dismantling for cleaning purposes and clearing the packings.
6.4.1.5	The distillation column SHALL be gas tight and leak free.
6.4.1.6	The distillation column SHALL be insulated to avoid heat losses.

Nr.	Reactive Distillation Column Design Requirements
6.4.2.1	The reactor SHALL consist out of three (main) compartments: - The void spaces at the top; - Supported packing bed; - The sump.
6.4.2.2	The pressure drop over the distillation column SHALL be measured using pressure gauges and a differential pressure transmitter.
6.4.2.3	The temperature profile over the distillation column SHALL be measured using AT LEAST 7 temperature transmitters.
6.4.2.4	The distillation column temperature SHALL be controlled by thermostated oil circulating in the jacket.
6.4.2.5	The partial condenser of the top stream SHALL be connected to a scrubber to absorb the excess NH_3 and other gaseous compounds before being vented.
6.4.2.6	In case the distillation column operates under vacuum conditions, the gaseous stream (i.e. from the gas-liquid separator) SHALL pass through a vacuum pump before being vented either directly or via a scrubber.
6.4.2.6	The required reboiler duty (1 kW) SHALL be supplied at the sump using an appropriate heat source (e.g. jacketed oil circulation or electrical jacket).

Nr.	Reactive Distillation Column General User Requirements
6.4.3.1	The distillation column SHALL be able to operate at temperatures between 50 and 180 °C.
6.4.3.2	The distillation column SHALL be able to operate at pressures between intermediate vacuum (~mbar) and 8 bara.
6.4.3.3	The distillation column SHALL be able to operate at liquid flowrates 1 – 10 L/h.
6.4.3.5	The distillation column and all wetted parts SHALL be resistant to low pH values 2-4.
6.4.3.6	The distillation column SHALL have a lifetime of AT LEAST 5 years of 24/7 continuous operation, with respect to corrosion resistance, mechanical stability, etc.
6.4.3.7	The distillation column SHALL be robust and functional to allow to be multiple times easily assembled and disassembled by the operator.
6.4.3.8	The distillation column SHALL have spare parts of critical components (e.g.: fittings for liquid inlet & outlets etc.).
6.4.3.9	The sump of the distillation column SHALL have a level indicator and a level controller.
6.4.3.10	Pressure safety valve SHALL be installed at the top of the distillation column.
6.4.3.11	A blow down valve in combination with a restricted orifice and a flow meter SHALL be installed at the top of the distillation column to allow safe release of the gas phase.

6.5 Reactive distillation column setup technical design

In the following tables, the requirements and preferences for the setup around the reactive distillation column are presented.

Nr.	Reactive Distillation Column Setup Requirements
6.5.1.1	The reactive distillation column setup SHALL consist of the following sections: 0. Utilities; 1. Liquid feedstock line to the column; 2. Liquid reflux to the top of the column; 3. Liquid distillate product stream;

	4. Gas lines to the scrubber; 5. Gas lines to the vacuum pump; 6. Gas-liquid separator; 7. Sump heater; 8. Bottom product discharge.
6.5.1.2	Section 0. Utilities of the distillation column setup SHALL feature a sensor, to be placed inside the setup to detect any possible NH_3 (or any flammable compound) leakages to the atmosphere inside the space of the setup, and must be connected to an alarm system.
6.5.1.3	Section 1. Liquid feedstock charge to the distillation column SHALL contain a transportable buffer storage (20 L), a pump (e.g. dosing pump) to allow feeding the reactor and a liquid flow meter. Moreover, the liquid feed SHALL be heated to the required temperature before entering the column.
6.5.1.4	Section 2. The liquid reflux line SHALL contain a dosing pump to allow recirculation of the liquid effluent of the top gas-liquid separator to the top of the distillation column. In addition, a liquid flow meter/indicator should be installed in the discharge side of the pump. The reflux ratio should be controlled.
6.5.1.5	Section 3. The liquid distillate product stream flow rate SHALL be controlled via the reflux ratio, but it should also have the functionality of continuous withdrawal of the liquid fraction of the top gas-liquid separator as distillate.
6.5.1.6	Section 4. Gas line from the top of the gas-liquid separator SHALL be directed to the scrubber before heading to the vent to remove excess of undesired gasses (e.g. NH_3).
6.5.1.7	Section 5. In case the distillation column will operate under vacuum conditions, the gas line from the gas-liquid separator SHALL pass either directly through the vacuum pump or after being washed in the scrubber before being vented
6.5.1.8	Section 6. The gas-liquid separator and the column SHALL be equipped with a controlled N_2 purge mechanism to flush the lines and the column.
6.5.1.9	Section 7: To provide sufficient boil up ratio, the sump of the distillation column SHALL be heated using an adequate heating source (1kW) (e.g. jacketed oil circulating or electrical jacket around the sump).
6.5.1.10	Section 8. The product discharge of the distillation column SHALL contain two buffer storage vessels with a storage capacity of AT LEAST twice the content of feedstock vessels (40 L), and a pump to transfer the contents of the reactor to the storage vessels or an external setup. The buffer vessels SHALL be equipped with pressure safety valves to release any gas build-up in the vessels to the vent.

Nr.	Reactive Distillation Column Setup & Control System Requirements
6.5.2.1	The distillation setup SHALL be assembled in a frame with lockable wheels that allows the setup to be movable. This means that it can be easily disconnected and reconnected for transport through laboratory doors. In addition, adjustable feet should be placed for stable final placement during operation. The whole setup will be contained by the frame when disconnected.
6.5.2.2	When operating the distillation setup, it SHALL not exceed a noise limit of 80 dB.
6.5.2.3	The distillation setup SHALL contain computer accessories in which the control software is installed and operative. The computer SHALL be integrated in distillation setup.
6.5.2.4	The operator SHALL be able to easily reach the instruments and sample points in the distillation setup manually for maintenance and modification purposes.
6.5.2.5	Sufficient lighting SHALL be mounted in the setup to facilitate operation.
6.5.2.6	The distillation setup SHALL include a control system to operate the setup, incl. hardware and software.
6.5.2.7	The distillation setup SHALL be fully automated, i.e., it shall be able to record data from sensors autonomously, and run unattended without the action of an operator (continuous operation).

6.5.2.8	The distillation setup SHALL be able to be operated remotely through an internet connection.
6.5.2.9	The distillation setup SHALL have a data-logging system for all the sensors of the setup to record all variables measured during operation.
6.5.2.10	The distillation setup SHALL record all available raw data from the installed sensors.
6.5.2.11	The distillation setup SHALL record all data on a hard disk, so that, in case of a power failure, the loss of data shall be of maximum 1 minute.
6.5.2.12	The distillation setup SHALL have spare parts available for AT LEAST 1 year after delivery and SAT.
6.5.2.13	The distillation setup SHALL be operated by TNO personnel at the chosen premises in which the setup will be delivered and installed.
6.5.2.14	The distillation setup SHALL be operated according to the TNO regulations of the chosen premises.
6.5.2.15	The distillation setup SHALL feature buttons for emergency stop of the operation that are easily reachable by the operators.
6.5.2.16	The distillation setup SHALL feature pressure relief valves or a similar system to prevent a dangerous overpressure in any part of the system.
6.5.2.17	The distillation setup SHALL feature leak trays or drip trays to allow the collection of any possible spilled liquid or substance from the setup.
6.5.2.18	All piping and tubing in the distillation setup SHALL be easily exchangeable. When applicable, for stainless steel piping, it is highly preferred to have Swagelok Imperial tubing in the distillation setup, as it is the current standard at the TNO premises.
6.5.2.19	The distillation setup SHALL feature a status light that is easily visible, with three different colours: - Green light: normal operation; - Orange light: setup in operation and off the setpoints (e.g. over-pressure, over-temperature); - Red light: critical alarm indicating failure conditions (e.g. leaks, column malfunctioning). The lights of the status lights do NOT blink or flash, i.e., are continuously on or off. In addition, a buzzer in the range of 70-100dB will be added to alert operators when the setup is operating at failure conditions.
6.5.2.20	The distillation setup SHALL alert the operators in case of an alarm with a sound and lighting system.
6.5.2.21	The control system of the distillation setup SHALL allow the definition of different situations, like Emergency Shutdown, or Power cut, that are triggered by specific alarms, and prompt actions in the system to safely stop the setup operation.
6.5.2.22	All error codes, alarm situations and warnings SHALL be recorded and logged into the system.
6.5.2.23	The control software interface SHALL be open source for the TNO personnel to have access and be able to modify it. It is highly preferred to have as control interface environment the software LabVIEW, as it is the current standard at the TNO premises.

The tenderer is required to provide an answer for the following preference:

Nr.	KW3 Hydrogenation reactor distillation setup technical design
KW3	The proposed PFD for the distillation setup (chapter 8 Appendix) is an initial suggestion to start with the design of the installation. Given the programme of requirements for the distillation setup, it is expected from the tenderer to provide a basic preliminary conceptual design for the distillation setup,

	complying with the mentioned list of technical requirements, that comprises the 9 abovementioned sections of the distillation setup. The tenderer must provide the following: • a basic conceptual design of the distillation setup; • a basic preliminary PFD for the distillation setup; • information about components and parts that will be in contact with the liquid mixture (e.g.: pipelines, valves, T-pieces, vessels, sensors, pumps, etc.); • a list of components with spare units that are necessary for the distillation setup; The key highlights of the design must be presented, along with the main advantages and characteristics. Address the challenges and solutions in the design, and the motivation to any proposed modifications to the presented PFD for the distillation setup (chapter (Appwendix T02) Provide information about the reasons to choose the selected components. Please be aware that it is not the intention to have a detailed and complete engineering design, but just the main guidelines and the strategy to follow during the design phase to come up with a successful setup.
	The entire answer should be concise, easily readable and not too extensive. Preliminary sketches and diagrams can also be part of the answer.

7 Abbreviations and definitions

Shall	:	Statements is mandatory and can only be waived with the formal approval of TNO.
Will	:	Statements that should be interpreted as fact.
Hazardous material	:	Hazardous materials are either explosive, flammable or toxic to people and the environment.
ATEX directive	:	Directive for electrical, electronic and mechanical equipment intended for use in Explosive ATmospheres. The European directive which was subsequently included into the Dutch legislation (Warenwet and Arbowet).
EMC directive	:	Directive for electrical and electronic equipment does not generate or is affected by electromagnetic disturbance which was subsequently included in the Dutch legislation (Warenwet and Telecommunicatiewet).
PED directive	:	Pressure Equipment Directive which was subsequently included into the Dutch legislation (Warenwet). European directive intended for the design, fabrication and use of pressure equipment above 0.5 bar.
LVD directive	:	Directive for electrical and electronic equipment with a voltage rating between 50 – 1000 VAC and 75 – 1500 VDC which was subsequently included into the Dutch legislation (Warenwet).
NET	:	Negative Emission Technologies
n	:	Normal
CCU	:	Carbon Capture & Utilisation
PFD	:	Process Flow Diagram
FAT	:	Factory Acceptance Test
SAT	:	Site Acceptance Test

8 Appendix

Draft of both setups

WP3 CCU CHARLIE
NET lab_PID_V5.vsd›