1 Project description

Name organisation	TNO
Name program	Sourcing of Skids
Tender	European public sourcing project

Project name	Electrochemical reactor + setup
Project Number	175
Division	NETLAB

2 Project Introduction

Within the NET Lab venture, TNO intends to realise experimental test stations for the testing of different negative emission technologies, focusing specifically on direct air capture. One of the activities is based on CO_2 absorption.

The aim of the present project is to develop and realise a novel process for the processing of CO_2 in an electrochemical device. The name of this electrochemical process is CODEC.

The CODEC process must be able to process CO_2 captured from a previous absorption process.

3 Project Background

The goal of TNO with the NET Lab 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 combined with CCU projects, and can also be used to try different prototypes in industrially relevant conditions by different parties. 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 level for a final industrial implementation to realise the climate goal of not surpassing the 1.5° C warming.

The three different technologies to be tested in the NET Lab are the following:

- Activity 1: Absorption;
- Activity 2: Adsorption test street;
- Activity 3: Carbon Capture and Utilisation; CHARLIE & SERENA processes, that are integrated CO_2 capture & conversion processes.

The present tender deals with Activity 1, '*Absorption'*, and Activity 3 '*CCU'*, more specifically, for the SERENA process.

4 Scope and deliverables

The scope of the present project is to engineer, manufacture, transport and install a demonstration unit capable of processing an inlet rich CO_2 aqueous solution, with a total CO_2 inlet of 100 g CO_2 /h using electrolysis. The demonstration unit shall primarily consist of:

- the electrochemical reactor,
- and a setup around it,
- with all the necessary interconnected and self-contained skid units with individual connections to the site supplied utilities.

The tenderer must deliver commercially available GDEs for the electrochemical reactor, in accordance with the list of requirements for the CODEC Reactor, in chapter 6.2.

4.1 Exclusions

The following will be excluded from the scope of supply:

- The Gas Diffusion Electrode (GDE) **design** is OUT OF THE SCOPE for the tenderer.

4.2 Scope, and content of the contract

The Contract (Electrochemical reactor + 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 – demonstration unit;

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 demonstration unit.

4.3 End result/deliverable

The result of the project is the commissioned and demonstrated demonstration unit according to the requirements. Next to the demonstration unit, the supplier will need to 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.

All above described documents 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 be part of the HAZOP sessions).

As part of detailed engineering, procurement and construction:

- P&ID, layout drawing, equipment drawings;
- Instruments data sheets;
- Analysers data sheets;
- Factory Acceptance Test – PLAN;
- Operational manual;
- Maintenance manual;
- All above described documents will be send to TNO for approval.

5 Functional description of the unit

5.1 CODEC Reactor

5.1.1 CODEC Process Description

Confidential information

5.1.2 CODEC Reactor Principle

Confidential information

5.1.3 CODEC Reactor configurations

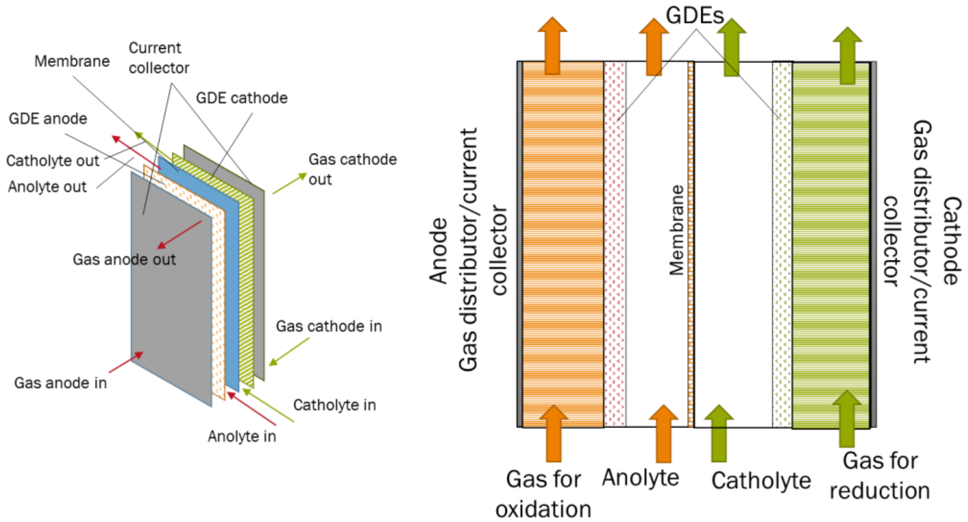
In the following illustrations, several possible reactor configurations for the CODEC process are presented.

The principle of the design of the CODEC reactor is that it allows different configurations. These configurations are the so-called Options #1, #2, #2.1 and #2.2. The idea is that, having as base case for the reactor design Option #1 (2 electrolyte chambers and 2 gas chambers, one GDE as the cathode, and one GDE as the anode and a membrane to separate the electrolyte chambers), the switch between the different options is easy and straightforward, requiring the minimal amount of modifications in the reactor.

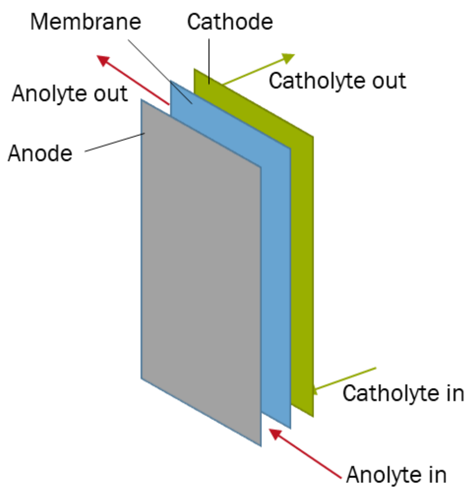
The fact that Option #1 has been chosen as the base case is because it is the most complex configuration, and has the highest number of inlets & outlets of all the options. The base case for the design of the CODEC reactor will be the Option #1 from the several reactor configurations, i.e., 2 electrolyte chambers and 2 gas chambers, using one GDE as the cathode, and one GDE as the anode and a membrane to separate the electrolyte chambers.

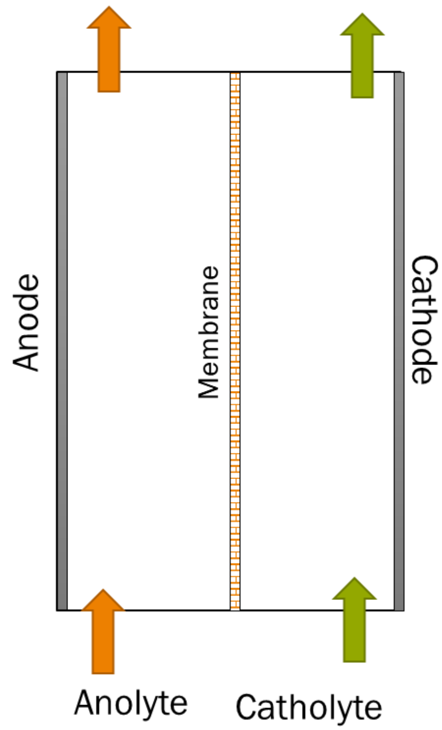
Please note that the below presented drawings are illustrative, and are meant to show the most basic principles of the design.

- ***Option #1***: GDE with gas chamber + electrolyte chamber:
    - Base case for the CODEC Reactor design;
    - At least 2 liquid inlets + at least 2 liquid outlets;
    - At least 2 gas inlets + at least 2 gas outlets;
    - The current collector for the GDE can also serve as a gas flow distributor that provides mechanical support.

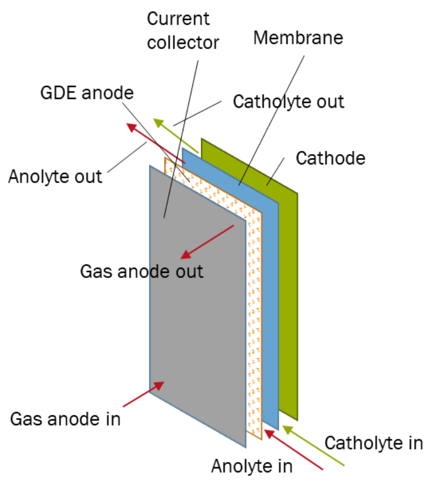


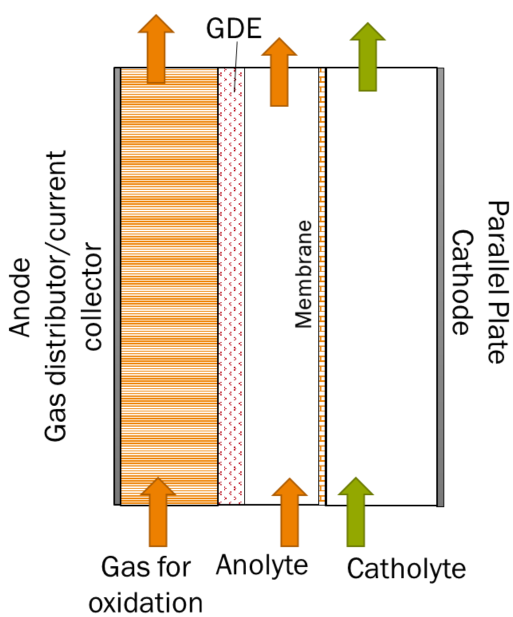
- ***Option #2***: Flow-by configuration with metal plate (i.e. parallel plate):
    - At least 2 liquid inlets + at least 2 liquid outlets;
    - No gas inlet or outlets;
    - Current collector in the back of the cell.



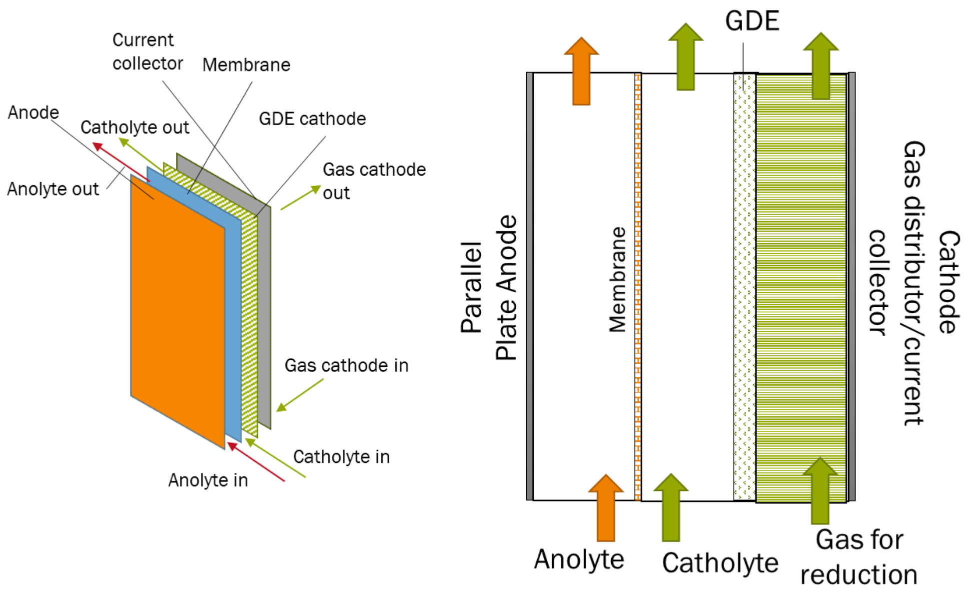


- ***Option #2.1***: Anode GDE with gas chamber + anolyte chamber + Cathode Parallel Plate:
    - At least 2 liquid inlets + at least 2 liquid outlets;
    - At least 1 gas inlet + at least 1 gas outlet;





- ***Option #2.2***: Cathode GDE with gas chamber + catholyte chamber + Anode Parallel Plate:
    - At least 2 liquid inlets + at least 2 liquid outlets;
    - At least 1 gas inlet + at least 1 gas outlet;



5.2 CODEC Setup

5.2.1 CODEC Process Description

The PFD for the CODEC setup can be found in File 1 of the Appendix,'*20200924- A1 CODEC setup_v3.pdf*'.

The CODEC setup includes two recirculation loops, with a buffer storage vessel to contain the anolyte and catholyte (VS-101, VS-201), and they go through the anode and cathode compartment, respectively. Both storage vessels for the electrolyte are jacketed vessels, with a connection to a thermostatic bath for cooling or heating. They also have a liquid level controlling system. The contents of the anolyte vessel (VS-101) can be transferred to the catholyte vessel (VS-201) through a selectable 3-way valve, and the contents of the latter can be transferred to a final discharge vessel (VS-601) using a 3-way valve as well. This discharge vessel serves as a buffer vessel that can be transferred outside of the setup via a pump, P-602.

There are various gas supply lines: two of those, containing carrier gas, an inert gas (N_2, Ar, etc.), go each one to one of the electrolyte vessels, to purge any possible gas formed from the electrochemical reaction. Two other gas supply lines go through gas conditioning units (GC-304, GC-305), and feed the CODEC reactor in case of a GDE configuration. At the outlet of the gas lines, there are 3-way valves in each of the lines, going either an external analytical unit, for analysis, or to the vent.

Nota bene: the mentioned equipment in the above paragraphs (3-way valve), or arrangement of the various equipment units from the appended PFD are just a suggestion for the tenderer to do the design of the CODEC setup. The list of requirements that the CODEC setup design shall comply with can be found in chapter 6.3.

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 CODEC Reactor (section 6.2).
- Technical functional aspects for the CODEC setup (section 6.3).

The delivered goods need to comply with the following regulations:

Nr.	General regulations requirements
6.1.1	The unit 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 unit SHALL be in line with international engineering standards.
6.1.4	The unit SHALL comply with all internal TNO regulations, in particular with safety.
6.1.5	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 Project plan and implementation

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

- The design phase:
    - In the design stage, 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 (CODEC Reactor + setup) SHALL be ready BEFORE September 1st 2021.
6.1.1.5	The overall plan for the manufacturing and delivery of the CODEC installation (reactor + 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. *CODEC Reactor design* - T3. *CODEC setup conceptual design* - T4. *CODEC setup engineering design* - T5. *CODEC setup 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 reactor 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 the design 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, ‘*CODEC Reactor design’*, is carried out by the tenderer, and will be the design of the electrochemical reactor of CODEC. All possible IP generated with the design of the CODEC Reactor WILL remain property of TNO.
6.1.1.10	In Task 2, ‘*CODEC Reactor design’*, in case of a third party company that takes care of the CODEC Reactor design, the tenderer SHALL involve this third party company in the discussions with TNO for the design of the electrochemical reactor of CODEC. As well, all IP generated with the design of the CODEC Reactor still remains property of TNO, regardless the involvement of a third party.
6.1.1.11	Task 3, ‘*CODEC setup 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 it 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, ’*CODEC setup engineering design*’, is responsibility of the tenderer, and it should have as output the engineering design of the CODEC setup 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 is the P&ID of the CODEC setup - Output 4.2 is the Design document
6.1.1.13	Task 5, ’*CODEC setup 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 reactor manufacturing*', is responsibility of the tenderer, and consists of the assembling and building of the CODEC setup, as well as the manufacturing of the CODEC Reactor. A setup layout diagram and a detailed drawing of the CODEC Reactor will be provided to TNO by the tenderer.
6.1.1.18	Task 9, '*Automation system*', is responsibility of the tenderer, and consists of the creation of the automation system for the CODEC setup, as well as its implementation in the constructed skid, incl. alarms, wiring, cabinet installation, etc.. A manual of control system will be provided together with the 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 machine, 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 skid by TNO personnel. The training SHALL take place at the location where the skid is 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;
6.1.2.2	A Site Acceptance Test (SAT) SHALL be performed at TNO after delivery. Following a successful SAT, TNO will test the skid 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 proposal. 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 (Anolyte vessel transfer to Catholyte vessel, and the latter to the Catholyte Discharge vessel) 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 CODEC reactor will be cautiously examined to evaluate the robustness and flexibility to switch between the different reactor options, and for the facile exchange of membranes and electrodes (parallel plates and/or GDEs). The reactor must ensure no leaks and be gas tight, regardless of the chosen configuration

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 skid, the written approval must be in the form of a purchase order issued by TNO. When the change affects specifications about the delivered skid, 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 and Time Schedule 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 in 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, etc.; • 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 CODEC reactor technical design

In the following tables, the requirements and preferences for the electrochemical reactor of the CODEC reactor are presented.

Nr.	CODEC Reactor Requirements
6.2.1.1	The CODEC reactor SHALL have a total projected electrode area of AT LEAST 0.100 m^2 (1000 (one thousand) cm^2), either in a stack or in a single cell.
6.2.1.2	*Confidential information*
6.2.1.3	*Confidential information*
6.2.1.4	The CODEC reactor SHALL be able to operate at a current density between 500 – 15000 A/m^2, and with a cell voltage of than 0-20 V DC.
6.2.1.5	The base case for the design of the CODEC reactor SHALL be the Option #1 from the several reactor configurations, i.e., 2 electrolyte chambers and 2 gas chambers, using one GDE as the cathode, and one GDE as the anode and a membrane to separate the electrolyte chambers: - This entails the design for AT LEAST 1 gas inlet and AT LEAST 1 gas outlet per gas chamber, and AT LEAST 1 liquid inlet and 1 liquid outlet per electrolyte chamber; - This leaves the reactor to have AT LEAST 2 gas inlets and AT LEAST 2 gas outlets, and AT LEAST 2 liquid inlets and 2 liquid outlets, in total.
6.2.1.6	The design of the CODEC reactor SHALL accommodate the easy and facile transformation between Option #1 (base case), Option #2 as well as Option #2.1 and Option #2.2.

6.2.1.7	Regardless the chosen reactor configuration, the CODEC reactor SHALL be able to run and ensure a safe operation introducing AT LEAST 2, 1 or no gas streams into the reactor.
6.2.1.8	The CODEC reactor SHALL allow the use of different electrode materials for different reactions.
6.2.1.9	In the CODEC Reactor, the different electrode materials SHALL be easily exchangeable for the operator.
6.2.1.10	The CODEC reactor SHALL be gas tight and leak free.

Nr.	CODEC Reactor Design Requirements
6.2.2.1	The CODEC reactor SHALL allow the installation of a membrane to separate the electrolyte chambers, and SHALL be mechanically supported - Suggestion: to improve the mechanical support of the membrane, flow spacers in the electrolyte chambers can be used.
6.2.2.2	The inter-electrode distance SHALL be between 2.0 – 8.0 mm.
6.2.2.3	The gas chamber SHALL have a thickness of 1.0 – 4.0 mm.
6.2.2.4	In case of a stack and not a 1000 cm^2 (total projected electrode area) single cell reactor design for the CODEC reactor, the max number of cells SHALL be 5 (i.e., 5 single cells of 200 cm^2 electrode area).
6.2.2.5	In case of a stack and not a 1000 cm^2 (total projected electrode area) single cell reactor design for the CODEC reactor, the stack configuration SHALL be bipolar.
6.2.2.6	In case of a stack and not a 1000 cm^2 (total projected electrode area) single cell reactor design for the CODEC reactor, the gas and liquid inlets SHALL be in parallel for all cells, and not in series (i.e., not being introduced consecutively from one cell to the next).

Nr.	CODEC Reactor General User Requirements
6.2.3.1	The CODEC reactor SHALL be able to operate at pH between 1 and 14.
6.2.3.2	The CODEC reactor SHALL be able to operate at temperature between 10 – 80° C.
6.2.3.3	The CODEC reactor SHALL be able to stand pressures up to 5 bar(a).
6.2.3.4	The CODEC reactor SHALL be able to operate at a pressure of 1 – 2 bar(a).
6.2.3.5	The CODEC reactor SHALL be able to operate at flowrates 30 – 200 L/h.
6.2.3.6	The electrolyte compartment and possible flow spacers of the CODEC reactor SHALL be resistant to CO_2, CO, O_2, H_2, formic acid, methanol, toluene, water, HCO_3^-, CO_3^{2-}, NaCl, NH_3, NH_4^+, SO_3^{2-}, SO_4^{2-}, NaOH, KOH, LiOH (2 M), H_2SO_4 (1 M), HCl (1 M), methyl diethanolamine, aminomethyl propanol; - Usual conditions: presence of OH^-, HCO_3^-, CO_3^{2-}, K^+, Na^+ (pH = 4 – 12). - Suggested material for flow spacers: polypropylene;
6.2.3.7	The CODEC reactor SHALL have a lifetime of AT LEAST 5 years of 24/7 continuous operation, with respect to corrosion resistance, mechanical stability, etc.; - For specific components (membrane, electrodes), this requirement does not apply.
6.2.3.8	The gas chamber and possible gas flow distributor SHALL be resistant to air, H_2O, N_2, Ar, CO_2, CO, O_2, H_2.
6.2.3.9	The CODEC reactor SHALL be robust and functional to allow to be multiple times easily assembled and disassembled by the operator.
6.2.3.10	The electrodes and membranes of the CODEC reactor SHALL be able to be easily replaced.
6.2.3.11	In the CODEC reactor, each electrode SHALL have a current collector, not in contact with electrolyte.

6.2.3.12	In the CODEC reactor, each electrode SHALL have enough current connections to ensure a good and homogeneous electric potential and electric current distribution over the electrode.
6.2.3.13	The CODEC reactor SHALL accommodate membranes 100-300 μm thick.
6.2.3.14	The CODEC reactor SHALL accommodate GDEs of a certain thickness, that will be decided on the design phase, and the range will be 50-300 μm.
6.2.3.15	The CODEC reactor SHALL accommodate parallel plate electrodes.
6.2.3.16	The CODEC reactor SHALL have spare parts of critical components (e.g.: fittings for liquid inlet & outlets, current collectors, flow spacers, etc.).
6.2.3.17	The CODEC reactor SHALL allow the use of flow spacers in the electrolyte chambers to support both the GDE and the membrane.

Nr.	**CODEC Reactor, Material Requirements**
6.2.4.1	*Confidential information*
6.2.4.2	*Confidential information*
6.2.4.3	*Confidential information*
6.2.4.4	*Confidential information*
6.2.4.5	*Confidential information*
6.2.4.6	*Confidential information*
6.2.4.7	*Confidential information*

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

Nr.	**KW2 CODEC reactor technical design**
KW2	For the CODEC Reactor, it is highly preferred to have one single cell reactor with a total projected electrode area of AT LEAST 0.100 m^2 (1000 cm^2). The tenderer needs to provide: *“a simple conceptual reactor design for a single cell of 1000 cm^2 total projected electrode area.”* The key highlights of the design must be presented, along with the main advantages and characteristics, and how the phenomena listed below are taken into account into the design. Given these dimensions (1000 cm^2), lots of challenges appear in the reactor design, especially considering the use of GDEs. Address these challenges and advise solutions in the design. Provide information about the flexibility of the proposed solution. The following phenomena need to be taken into account in the reactor design: - The easy and facile switch from Option #1 to #2, as well as to #2.1 and #2.2, requiring the minimal number of modifications to the single cell; - The pressure difference between the gas side and the electrolyte side in the GDEs throughout the height of the reactor should be preferably minimised and kept below 150 mbar throughout the height of the reactor; - The homogeneity of the electrolyte flow in the liquid compartments must be maximised, minimising the dead zones (zones with stagnant liquid) in the compartment; - The mechanical stability of the GDE must be ensured to prevent any rupture or breakage;

	- The current and electric potential distribution in both electrodes must be homogenous in the x (width) and y (height) directions of the electrode; - All the parts in contact with electrolytes of the CODEC reactor are highly preferred to be metal free (except electrodes). Please be aware that it is not the intention to have a detailed and complete reactor design, but just the main guidelines and the strategy to follow during the design phase to come up with a successful electrochemical reactor. Please note that the demanded reactor design is specifically referring to a single cell reactor with a total projected electrode area of AT LEAST 0.100 m^2 (1000 cm^2). In case of presenting a design for a reactor stack of a total projected electrode area of AT LEAST 0.100 m^2 with various cells, the presented answer will still be evaluated, but will be less well judged in comparison with a design for a single cell reactor of 0.100 m^2. It is reminded that the presented design for a reactor stack SHALL comply with the sub-list of requirements 6.2.2.
	The entire answer should be concise, easily readable, and not too extensive. Preliminary sketches can also be part of the answer.

6.3 CODEC setup technical design

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

Nr.	CODEC setup Requirements
6.3.1.1	The CODEC setup SHALL consist of the following **sections**: 0. Utilities 1. Anolyte loop 2. Catholyte loop 3. Gas lines 4. Power supply 5. Water bath 6. Catholyte discharge.
6.3.1.2	The Section 0. Utilities of the CODEC setup SHALL feature a sensor, to be placed inside the skid to detect any possible CO (or any flammable compound) in the atmosphere inside the space of the skid, and must be connected to an alarm system.
6.3.1.3	The Section 1. Anolyte loop of the CODEC setup SHALL contain a buffer storage jacketed vessel, a pump to allow recirculation of the anolyte through the anolyte chamber of the CODEC Reactor, a liquid flow meter, temperature, pressure, pH and electrical conductivity sensors, and a system to transfer the electrolyte to Section 2. Catholyte loop.
6.3.1.4	The Section 2. Catholyte loop of the CODEC setup SHALL contain a buffer storage jacketed vessel, a pump to allow recirculation of the catholyte through the catholyte chamber of the CODEC Reactor, a liquid flow meter, temperature, pressure, pH and electrical conductivity sensors, and a system to transfer the electrolyte to Section 6. Catholyte discharge.
6.3.1.5	Both Section 1 Anolyte loop, and Section 2 Catholyte loop SHALL have a system to easily take samples out of the anolyte and catholyte loop, and shall be inherently safe.
6.3.1.6	The anolyte and catholyte storage vessels VS-101 & VS-201 SHALL have a system to automatically regulate its liquid level.
6.3.1.7	The Section 3. Gas lines of the CODEC setup SHALL contain two gas conditioning units, that pre-treat the gas feeds to the anode and cathode chambers of the CODEC Reactor (in Options #1, #2.1 and #2.2), and a system to carry away all possible gases

	that may accumulate in the anolyte vessel VS-101, and catholyte vessel VS-201, as well as a system to take inline gas samples to an external analytical unit to analyse the gas composition of (1) gas outlet of the anode chamber; (2) gas outlet of the cathode chamber; (3) gas outlet of the anolyte vessel VS-101; (4) gas outlet of the catholyte vessel VS-201.

6.3.1.8	The gas conditioning units from Section 3 Gas lines of the CODEC setup SHALL allow the operator to choose the conditions of the outlet gas stream with the following parameters:
	- **Temperature**: 20 – 90° C;
	- **Pressure**: 1.0 – 2.0 bar(a);
	- **Total outlet flowrate**: 0 to AT LEAST 1.0 Nm^3/h;
	- **Water content (related to relative humidity):** 0 – 200 g H_2O/h;
	- **Composition**: up to three (3) different gases can be introduced: one carrier gas (N_2, air, Ar, etc.), which flowrate can go from 0 to at least 1.0 Nm^3/h ; and two (2) gas reactants (O_2, H_2, CO_2, CO, etc.).
	  - The flowrate range for each gas reactant inlet SHALL be from 0 to AT LEAST 0.5 Nm^3/h
	  - The gas conditioning unit SHALL allow the composition of a gas mixture composed of the carrier gas and two distinct gas reactants from 0 to 100%vol. for any of the gas species.

6.3.1.9	The Section 3. Gas lines of the CODEC setup SHALL be designed to carry away the H_2 that may accumulate in the catholyte vessel VS-201, and the gases from the anolyte vessel VS-101, and avoid any hazard of a high H_2 concentration inside any vessel. - It must be noted that, if a high flowrate of carrier gas is introduced in the electrolyte vessels, there is a risk of evaporating part of the solvent during operation.
6.3.1.11	The Section 3. Gas lines of the CODEC setup SHALL be able to detect and trigger an alarm in case the Ion Exchange Membrane inside the CODEC Reactor is ruptured, which can lead to a mixture of O_2 and H_2 in any of the electrolyte vessels. - Suggestion: an inline H_2 sensor in the gas outlet of the anolyte vessel VS-101 can be a solution.
6.3.1.12	The Section 3. Gas lines of the CODEC setup SHALL feature a draining system at the gas outlets of the CODEC Reactor (Options #1, #2.1, #2.2) that can handle a biphasic flow of gas + condensation or electrolyte. - Using GDEs, the electrolyte can flood the gas chamber, and due to the high gas flowrates, this electrolyte can be carried away and form a biphasic flow with the gas. Also, due to difference in temperature from inside the reactor to the gas outlet lines, some condensation of water can happen, thus leading as well to a biphasic flow.
6.3.1.13	The Section 4. Power supply of the CODEC setup SHALL feature a power supply connected with the CODEC Reactor that must provide AT LEAST 400 A and AT LEAST 15 V DC; - In case of a stack and not a 1000 cm^2 (total projected electrode area) single cell reactor design for the CODEC reactor, the power supply SHALL provide AT LEAST 400 A and AT LEAST 30 V DC.
6.3.1.14	The power supply from Section 4. Power supply of the CODEC setup SHALL be able to run in galvanostatic mode (constant current), and also in potentiostatic mode (constant voltage), and measure both electric current and voltage and record them in the data-logging system.
6.3.1.15	The Section 5. Water bath of the CODEC setup SHALL feature a water bath that has a cooling capacity of AT LEAST 1 kW, with a minimal temperature of 10° C.
6.3.1.16	The Section 5. Water bath of the CODEC setup SHALL feature a water bath that has a heating capacity of AT LEAST 2 kW, with a maximal temperature of 90° C.

6.3.1.17	The Section 6. Catholyte discharge of the CODEC setup SHALL contain a buffer storage vessel, and a pump to transfer the contents of the vessel to an external setup or container.
6.3.1.18	The storage vessels VS-101, VS-201 and VS-601 SHALL have a buffer capacity of AT LEAST 50 L.
6.3.1.19	The pumps P-106, P-206 and P-602 SHALL deliver a liquid flowrate of AT LEAST 30 – 150 L/h, and a differential head of AT LEAST 2 bar.

Nr.	CODEC setup, General User Requirements
6.3.2.1	The CODEC setup SHALL be able to operate at pH between 1 and 14 at room T.
6.3.2.2	The CODEC setup SHALL be able to operate at temperature between 10 – 80° C.
6.3.2.3	The CODEC setup SHALL be able to stand pressures up to 5 bar(a).
6.3.2.4	The CODEC setup SHALL be able to operate at a pressure of 1 – 2 bar(a).
6.3.2.5	The components and parts in contact with the electrolyte of the CODEC setup SHALL be resistant to CO_2, CO, O_2, H_2, formic acid, methanol, toluene, water, HCO_3^-, CO_3^{2-}, NaCl, NH_3, NH_4^+, SO_3^{2-}, SO_4^{2-}, NaOH, KOH, LiOH (2 M), H_2SO_4 (1 M), HCl (1 M), methyl diethanolamine, aminomethyl propanol; - Usual conditions: presence of OH^-, HCO_3^-, CO_3^{2-}, K^+, Na^+ (pH = 4 – 12).
6.3.2.6	In the CODEC setup, all parts and components in contact with the electrolytes SHALL be, when possible, metal-free.
6.3.2.7	The CODEC setup SHALL have a lifetime of at least 5 years of 24/7 continuous operation, with respect to availability of components, corrosion resistance, mechanical stability, etc., and be able to withstand a cyclic operation (e.g.: repeated loading and unloading of the different buffer vessels).
6.3.2.8	The CODEC setup SHALL have an uptime of AT LEAST 95% per year.

Nr.	CODEC setup, skid & control system requirements
6.3.3.1	The CODEC 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.
6.3.3.2	When operating the CODEC setup, it SHALL not exceed a noise limit of 80 dB.
6.3.3.3	The CODEC setup SHALL feature a computer, a screen and some keyboard + mouse (or touchscreen) in which the control software is installed and operative. The computer SHALL be integrated in CODEC setup, and be a functional part of the skid
6.3.3.4	The operator SHALL be able to easily reach the instruments and sample points in the skid manually for maintenance and modification purposes.
6.3.3.5	Sufficient lighting SHALL be mounted in the skid to facilitate operation.
6.3.3.6	The CODEC setup SHALL include a control system to operate the skid, incl. hardware and software.
6.3.3.7	The CODEC 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).
6.3.3.8	The CODEC setup SHALL be able to be operated remotely through an internet connection.
6.3.3.9	The CODEC setup SHALL have a data-logging system for all the sensors of the setup to record all variables measured during operation.
6.3.3.10	The CODEC setup SHALL record all available raw data from the installed sensors.
6.3.3.11	The CODEC 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.

6.3.3.12	The CODEC setup SHALL have spare parts available for AT LEAST 1 year after delivery and SAT.
6.3.3.13	The CODEC setup SHALL be operated by TNO personnel at the chosen premises in which the skid will be delivered and installed.
6.3.3.14	The CODEC setup SHALL be operated according to the TNO regulations of the chosen premises.
6.3.3.15	The CODEC setup SHALL feature buttons for emergency stop of the operation that are easily reachable by the operators.
6.3.3.16	The CODEC setup SHALL feature pressure relief valves or a similar system to prevent a dangerous overpressure in any part of the system.
6.3.3.17	The CODEC setup SHALL feature leak trays or drip trays to allow the collection of any possible spilled electrolyte or substance from the setup.
6.3.3.18	All piping and tubing in the CODEC setup SHALL be easily exchangeable. When applicable, for stainless steel piping, it is highly preferred to have Swagelok Imperial tubing in the CODEC setup, as it is the current standard at the TNO premises.
6.3.3.19	The CODEC setup SHALL feature a status light that is easily visible, with three different colours: - Green light: on and/or active (setup not in operation) - Orange light: active (setup in operation) and dangerous conditions - Red light: critical alarm The lights of the status lights do NOT blink or flash, i.e., are continuously on or off.
6.3.3.20	The CODEC setup SHALL alert the operators in case of an alarm with a sound and lighting system.
6.3.3.21	The control system of the CODEC 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.
6.3.3.22	All error codes, alarm situations and warnings SHALL be recorded and logged into the system.
6.3.3.23	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 CODEC setup technical design
KW3	The proposed PFD for the CODEC setup (chapter Appendix) is an initial suggestion to start with the design of the installation. Given the programme of requirements for the CODEC setup, especially those referred to Section 3, 'Gas lines', it is expected from the tenderer to provide a basic preliminary conceptual design for the CODEC setup, complying with the mentioned list of technical requirements, that comprises the 6 abovementioned sections of the CODEC setup. The tenderer must provide the following: • a basic conceptual design of the CODEC setup; • a basic preliminary PFD for the CODEC setup; • information about components and parts that will be in contact with electrolytes (e.g.: pipelines, valves, T-pieces, vessels, sensors, pumps, etc.);

	• a list of components with spare units that are necessary for the setup; • a preliminary solution to have a metal-free 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 CODEC setup (chapter 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 skid.
	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
CCU		Carbon Capture & Utilisation
GDE		Gas Diffusion Electrodes
PFD		Process Flow Diagram

DC	Direct Current
FAT	Factory Acceptance Test
SAT	Site Acceptance Test

8 Appendix

- File 1: PFD for the CODEC setup:

20200924- A1 CODEC setup_v3.pdf