Final report

1. Project details

Project title	CHOCO2LATE
File no.	64021-3206
Name of the funding scheme	EUDP 2021-II CO2-fangst, -udnyttelse og -lagring
Project managing company / institution	TK Energy Aps (Originally), (Later) Aalborg University
CVR number (central business register)	34898391
Project partners	TK Energy, Aalborg University, COWI, Aqueous Solutions
Submission date	27 March 2025

2. Summary

English:

CO_2 will be a key resource in the green transition for two main reasons; 1) to carbon-offset hard-to-decarbonize sectors to reach carbon neutrality by 2050, and 2) to ensure the production of carbon-based fuels, chemicals, and materials in a carbon-driven PtX industrial setup. Paradoxically, despite the fact that we are fighting against climate changes due to CO_2 accumulation in the atmosphere, CO_2 scarcity is a real threat if we only count on biogenic CO_2 from point sources. Atmospheric CO_2 is an almost limitless CO_2 resource, and direct air capture (DAC) of CO_2 is the only long-term solution for providing sufficient carbon for the PtX industry (CCU) and to achieving net CO_2 negativity (CCS) longterm. Despite the currently higher costs of DAC over point source CO_2 capture, DAC is likely to become an inflection point in the long term due to the unlimited resource. In fact, projections forecast that 80 % of the industrially needed CO_2 will come directly from the air. DAC pilot facilities are currently in operation, but the full potential of DAC is still challenged by high consumption of energy and water, negative environmental effects of absorbents, and the use of carbon-based fuels for sorbent regeneration, which negatively offset the CO_2 capture efficiency. Thus, there is an unmet need for technical solutions, which can improve efficiencies and versatility of DAC systems.

The purpose of the project is to develop an engineered solution that is both technically feasible and economically attractive to capture CO_2 directly from air. When successful, such technology can significantly mitigate the future risk of CO_2 scarcity for PtX purposes. The following are the main findings of the project:

- The project finds that eliminating make-up water by relying on air humidity is feasible and could improve process efficiency.

- The project finds that adding burnt lime (CaO) directly to the circulating scrubber liquid (original objective) is not practical, as it leads to poor reaction efficiency and difficulties in separating solid byproducts.
- The project finds that potassium hydroxide (KOH) is preferred over sodium hydroxide (NaOH) due to its broader operational space based on relative humidity levels.
- The project finds that operating a CO_2 scrubber without managing make-up water leads to solvent concentration variations throughout, which may/may not impact process control, kinetics, and capture efficiency. This should be further examined.
- The project finds that above a certain sorbent concentration, capture efficiency remains constant. However, a more concentrated solution can absorb significantly more CO_2 (preferable), but regeneration challenges could remain due to slow dissolution kinetics of $Ca(OH)_2$. (unpreferable). The trade-off should be examined.
- The project finds that KOH-based CO_2 capture achieves an efficiency of above 70 %, aligning with reported literature values.
- The project finds that lime mud formation is likely to be a major issue in the caustification process, making drying and solid sorbent handling difficult.
- The project finds that the reactivity of burnt lime (CaO) is affected by burning temperature, storage conditions, and impurities, impacting its suitability for the process.
- The project finds that CO_2 can be captured using a liquid calcium hydroxide ($Ca(OH)_2$) solution without alkalis, but separation and drying of $CaCO_3$ particles pose challenges.
- The project finds that wet CO_2 capture processes may present safety risks due to alkaline aerosols, requiring further risk assessments.
- The project finds that calcination in a hydrogen-rich atmosphere lowers reaction temperatures and increases reaction kinetics, making it a promising alternative to conventional calcination.
- The project finds that integrating direct air capture (DAC) with Fischer-Tropsch synthesis could achieve energy efficiency above 50 %, highlighting its potential for industrial-scale implementation.

Dansk:

CO_2 vil være en nødvendig ressource i den grønne omstilling af to hovedårsager; 1) at kompensere sektorer, der vil være svære at dekarbonisere for at opnå CO_2-neutralitet i 2050, og 2) for at sikre produktionen af kulstofbaserede brændstoffer, kemikalier og materialer i et kulstofdrevet industrielt PtX setup. Paradoksalt nok, på trods af klimafordringer grund for stor koncentration af CO_2 i atmosfæren, er CO_2-mangel en reel trussel, hvis vi kun indregner biogent CO_2 fra punktkilder. Atmosfærisk CO_2 er en næsten ubegrænset ressource, og CO_2-fangst direkte fra luften er den eneste langsigtede løsning til at levere tilstrækkeligt kulstof til PtX-industrien (CCU) og til at opnå netto CO_2-negativitet (CCS) på sigt. På trods af de nuværende højere omkostninger ved DAC i forhold til fangst fra punktkilder, vil DAC sandsynligvis blive et vendepunkt på lang sigt på grund af den ubegrænsede ressource. Faktisk forudsiger fremskrivninger, at 80 % af den industrielt nødvendige CO_2 vil komme direkte fra luften. Flere DAC-pilotanlæg er i øjeblikket i drift, men teknologiens fulde potentiale er stadig uforløst og udfordret af højt forbrug af energi og vand, negative miljøpåvirkninger fra sorbenterne og brugen af kulstofbaserede brændstoffer til sorbent-regenerering, som negativt påvirker CO_2 fangsteffektivitet. Der er således et stort behov for tekniske løsninger, som kan forbedre effektiviteten og alsidigheden af DAC-systemer.

Formålet med projektet var at udvikle en løsning, der både er teknisk mulig i stor skala og økonomisk attraktiv til at opsamle CO_2 direkte fra luften. Når en sådan teknologi lykkes, kan den i væsentlig grad mindske den fremtidige risiko for CO_2-mangel til PtX-formål.

- Projektet finder, at eliminering af vandtilsætning/fordampning er muligt, hvilket kan forbedre proceseffektiviteten.
- Projektet finder, at tilsætning af brændt kalk (CaO) direkte til skrubbervæsken ikke er praktisk, da det fører til lav reaktionseffektivitet og problemer med separation af faste biprodukter kan opstå.
- Projektet finder, at kaliumhydroxid (KOH) foretrækkes frem for natriumhydroxid (NaOH), da KOH er mere anvendelig i et bredere spektrum af relativ luftfugtighed.
- Projektet finder, at direkte læskning af kalk i skrubbervæsken resulterer i lav konverteringseffektivitet og kontaminering af det endelige kalk-produkt ($CaCO_3$).
- Projektet finder, at driften af en CO_2-skrubber uden tilsat vand vil medføre variationer i solventkoncentration, hvilket muligvis kan påvirke proceskontrol og fangstkinetik. Det skal eftervises. Variationerne vil være afhængig af lokation.
- Projektet finder, at en mere koncentreret skrubbervæske kan absorbere markant mere CO_2 (tilskyndet), men at regenerering kan blive en udfordring på grund af langsom opløsning af læsket kalk $Ca(OH)_2$ (ikke tilskyndet).
- Projektet finder, at dannelsen af kalkslam kan være et stort problem i kaustificeringsprocessen, hvilket gør tørring og håndteringen kalken besværlig og omkostningstung.
- Projektet finder, at reaktiviteten af brændt kalk (CaO) afhænger af brændingstemperatur, opbevaringsforhold og urenheder, hvilket påvirker materialets egnethed til processen.
- Projektet finder, at CO_2 kan opsamles ved reaktion med en flydende calciumhydroxid ($Ca(OH)_2$) opløsning, men separation og tørring af $CaCO_3$-partikler skaber udfordringer.
- Projektet finder, at KOH-baseret CO_2-opsamling opnår en effektivitet på over 70 %, hvilket stemmer overens med resultater fra litteraturen.
- Projektet finder, at våde CO_2-opsamlingsprocesser kan udgøre en sikkerhedsrisiko på grund af basiske aerosoler, hvilket kræver yderligere risikovurderinger, evt. også en vandskrubber.
- Projektet finder, at kalcinering i en brintrig atmosfære sænker reaktionstemperaturen og øger reaktionshastigheden, hvilket gør det til et lovende alternativ til konventionel kalcinering.
- Projektet finder, at integration af direkte luftfangst (DAC) med Fischer-Tropsch-syntese kan opnå en energieffektivitet på over 50 %, hvilket fremhæver potentialet for industriel skalaimplementering.

Lav en kort sammenfatning af projektforløbet på basis af oplysningerne fra afsnit 1-5 (projektgennemførsel, ressourceforbrug, kommercialisering, risikovurdering og øvrige oplysninger):

When the project was launched it was considered a pioneer project in a Danish context. At least, to the best of the partners' knowledge, this was the first direct air capture demonstration project in Denmark. We would like to thank EUDP for the timely support.

The project was originally designed in three phases:

- A designing, construction, and validation phase of an air scrubber. The air scrubber was be designed in collaboration with all partners and finally constructed at TK Energy's premises. The scrubber, slaker, and dryer will be constructed as separate units by TKE. For health, safety, and environmental reasons concrete flooring with safety showers were supposed to be installed. Collection of wastewater and neutralization of wastewater was planned. A separate basin/scrubber to avoid exposure of alkaline aerosols to surroundings was planned. None of the planned installations in this phase were implemented. Aqueous Solutions ApS (AS) performed thermodynamic calculations and process simulation as important input to support the scrubber and slaker design and operation. The deliverables (D2.1 and D2.2) by AS were handed in timely and satisfactorily. The remaining deliverables by TKE and COWI were not executed.

- A design and validation phase of an electric calciner operating with a hydrogen dominated atmosphere. In accordance with the project plan and budget, AAU invested in thermogravimetric analyzer capable of operated under a pure hydrogen atmosphere. With this instrument (which was slightly delayed due to a shortage of mass flow controllers, because of COVID), AAU assisted the calciner design phase by investigating the influence of various calcination atmospheres and conditions with the aim of lowering the calciner temperature. TK Energy was supposed to design and ceramic burner and construct a lab-scale calciner. The calciner was supposed to be installed at AAU for further testing and validation. AAU delivered the calcination literature review (D3.1). Based hereof, an invention disclosure was reported, and an IP pre-screening was performed. AAU also reported on calciner thermodynamics. AAU deliverables were performed timely and satisfactorily. The remaining deliverables by TKE were not executed.

- A process performance phase including TEA and LCA modelling of the DAC only system but also a future DAC-PtX system based on the results obtained during the course of the project. AAU delivered a TEA analysis of the DAC-PtX, based on Fischer-Tropsch synthesis. AAU also developed the LCA modelling framework, but LCA performance was never calculated due to the pre-termination of the project.

The project process has been very chaotic. The following table lists the main events from grant approval to project pre-termination.

Tabel 1 Time events in the CHOCO2LATE project

Time	Event
05-03-2021	Receipt for upload of original CHOCO$_2$late application.
02-09-2021	Receipt for upload of revised CHOCO$_2$late application.
09-12-2021	Receipt for undertaking of support from EUDP.
01-02-2022	Official start date.
06-10-2022	Official kick-off meeting. (8 months after official start date)
27-10-2022	Change request: New end date. (31-01-2024 → 30-09-2024).
31-10-2022	Change request approved.
06-03-2023	Collaboration agreement signed by all partners. (13 months after official start date)
13-03-2024	Change request: 1) New end date. (30-09-2024 → 30-09-2025). 2) Project leader change from Thomas Koch (TKE) to Thomas Helmer Pedersen (AAU). 3) New budget allocation requested.

09-04-2024	New project leader and end date approved. New budget allocation declined. Board decision needed due to the significance of the budget change.
12-04-2024	Meeting with EUDP to discuss the change request.
07-08-2024	TKE (original project leader) requests an exit from the project.
12-08-2024	Follow-up meeting with EUDP. It was agreed that THP should try to find new commercial partner(s), before submission of change request to the EUDP board in December.
15-11-2024	THP receives commitment from four new partners to enter the project. Co-financing secured. THP submits new change request for pre-screening to EUDP before presentation at the board meeting in December 2024.
27-11-2024	Notification from EUDP that the project needs further external review. THP reshapes the project application.
13-11-2024	THP submits new project application for external review.
09-01-2025	THP receives review for hearing. New date for board decision pushed to ultimo March.
28-01-2025	Final meeting with EUDP to discuss next steps.
05-02-2025	THP notifies EUDP to terminate the project.

Since the beginning of the project, DAC technology has experienced notable advancements in both development, deployment and investment. Today, 27 DAC plants have been commissioned worldwide, collectively capturing nearly (or only..) 0.01 million metric tons of CO_2 annually, with plans underway for at least 130 large-scale facilities, which could significantly increase this capacity. Government support in US has been substantial, with commitments exceeding USD 4 billion since 2020, including USD 3.5 billion allocated for developing four DAC hubs in the US. One such hub is based on Carbon Engineering technology, upon which this project was intended to innovate (air contactor and electric calciner). Very recently, Saudi Aramco launched (in collaboration with Siemens Energy) first DAC unit, capable of removing 12 tons of CO_2 annually. The technology behind remains unclear. Despite these advancements, challenges remain, primarily high costs and scalability concerns, underlying the need for continued innovation and supportive policies/and grant schemes to enhance DAC's role in achieving climate goals and position DK as a relevant player in the DAC arena.

Project objectives

The overarching objective of the project, as originally outlined in the application, focusing on developing and demonstrating a full process chain for capturing atmospheric CO_2 and converting it into liquid Fischer-Tropsch fuels. In a first phase, this project specifically focused on the capture part. The technical and commercial objectives included:

Technical objectives:

- Developing an innovative air scrubber with a sorbent that efficiently captures CO_2 from the air with minimal water loss and low energy consumption.
- Designing a hydrogen-fired calciner that regenerates the sorbent at a significantly lower temperature than conventional calciners, using only sustainable, CO_2-neutral fuels.
- Commission an air capture contactor that, when coupled with Fischer-Tropsch synthesis, can produce 10 kg/h of hydrocarbons, equivalent to 130 kW fuel output.
- Exploring integration with hydrogen and oxygen production via electrolysis for a fully renewable and sustainable process.
- Derisk challenges such as slow CO_2 absorption kinetics, scaling issues in the scrubber, high calcination temperatures, and aerosol elimination.

Commercial objectives:

- Ensuring the DAC-PtX process achieves a minimum fuel selling price of synthetic diesel or jet fuel at 8 DKK/L.
- Demonstrating the system's scalability to GW levels, making it commercially attractive to major energy companies.

3. Project implementation

The project period was extended twice (see Table 1), first by 8 months, then later by 12 months. The first extension was caused by delays in signing the collaboration agreement (e.g. key person left COWI early in the project), delays in deliveries of certain key parts (e.g. TGA to AAU) due to COVID. The second extension was requested due to the exit of the project leader and the desire to take the project activities in a slightly different direction by the remaining and new partners without changing the project objectives. The extension was granted was the project faced a pre-termination because budget allocations could not be granted.

4. Project results

Outcome related to WP2:

Originally, the air contactor (by TKE) used a direct contacting principle, in which a strong alkaline solution is directly contacted with air. The general observation is that it is indeed possible to capture CO_2 by the direct contact between air and a liquid solution of e.g. KOH or calcium hydroxide. Some observations, however, challenged the concept:

- When using calcium hydroxide, the captured CO_2 is in the form of very small $CaCO_3$ particles. Screening of these particles from the liquid process and drying them can be a major, energy-intensive task. Additionally, scaling of $CaCO_3$ on all surfaces of the process equipment is also a problem.
- CO_2 capture with wet processes may pose a safety risk due to alkaline aerosols. Therefore, an assessment of potential risks has been conducted, and a general HSSE plan has been presented.
- A dry route for CO_2 capture using CaO and $Ca(OH)_2$ has been experimentally conducted. It highlights possible methods as well as challenges that need to be addressed, such as thin-layer sorbents and deactivation after multiple cycles between CaO and $CaCO_3$. Ideas for solving these issues have been presented.
- A list of advantages and disadvantages of wet and dry processes is presented.
- Concepts for small-scale design testing of dry CO_2 capture are introduced. Capture kinetics were observed very slow.
- A technical solution to undercome the abovementioned challenges was presented to EUDP, and a change in project direction was requested. Unfortunately, the request could not be granted with a board decision. The lengthy process led to a project pre-termination.

Figure 1 Experimental tests for dry capture of atmospheric CO_2

One of the innovative elements of this project is to develop a CO_2 scrubber with a potential capture efficiency of 70 %, where the sorbent is based on KOH-$CaCO_3$, and to develop the necessary auxiliary equipment to dry, condition and deliver the $CaCO_3$ to an electric calciner. Carbon Engineering operates a demonstration plant for direct air capture using aqueous KOH as solvent. In this project a similar solvent but a different process concept is suggested. The new concept could potentially make DAC more economical. Based on an accurate thermodynamic model for aqueous solutions of salts, a new and simpler process concept is developed. This new process consists of fewer steps compared to the process applied by Carbon Engineering. The initial idea in the project is to avoid a separate slaker and add lime (CaO) to the circulating scrubber liquid. Alternatively, a separate slaker can be used. Lime will be added to the scrubber liquid and the suitable excess lime concentration to avoid homogenous nucleation to avoid formation of numerous small particles will be investigated.

Outcome related to WP3:

The first objective was to design a burner operating with a gaseous fuel dominated by hydrogen – produced from electrolysis. Early in the project, AAU demonstrated that a direct electric calciner (preferably operating with a hydrogen dominated atmosphere) was preferred over using hydrogen as a fuel. Hence, the focus was shifted to building an electric calciner (TKE). Many different designs were evaluated, but safety was always the major concern. AAU approached a third party, who was demonstrating a lab-scale rotating oven able to operate with a hydrogen atmosphere. In the early discussions, the cost of the unit was within the project budget, but gradually the cost increased by approx. 100 %. AAU stopped following this option. Finally, it was clear that the partnership did not have the capacity to build the calciner. TKE then left the project.

We have prepared a continuous review of existing DAC processes in relation to Task 3.1. The review summarizes the most common DAC methods, their energy consumption, technology maturity levels, etc. The review has also shown that calcination of lime in hydrogen has been investigated in the literature, but primarily with hydrogen as fuel.

An experimental proof-of-concept on calcination in hydrogen has been carried out with good results. The experimental work primarily consisted of investigating the influence of a hydrogen-dominated reaction atmosphere on the calcination temperature at which calcination begins, as well as the reaction kinetics associated with the release of CO_2 using a thermogravimetric analysis unit (TGA). The results of the TGA experiments show that the calcination temperature and reaction time are significantly lower when using a hydrogen-based atmosphere, which proves the initiating hypothesis in the project description.

It was decided to develop a model to help explain the experimental observations on the TGA. First, a transport model using the “Dusty Gas Model” diffusion has been developed. The model does not (yet) include gas phase or surface reactions on CaCO3 and CaO, only the calcination reaction itself. The model predicts a slightly faster calcination in gases with low atomic number but does not predict the rapid calcination in H2. It is therefore assumed that chemical reactions in the gas phase and on the surfaces are the main reason for the faster calcination in H2. Thermodynamic calculations confirm that the “water gas shift” reaction helps the calcination because H2 reacts with CO2. Thermodynamic and kinetic calculations of the calcination in N2 and H2 have been started. The open-source program Cantera is used for this purpose. Here gas phase reactions and

Outcome related to WP4:

The objective of this work package was to lay the foundation for the further development and commercialization of the technologies explored in the project. This involved a comprehensive assessment of system performance, environmental impact, and scalability to ensure feasibility for future implementation. Activities included process simulations by AAU to conduct a full system performance evaluation. This included establishing integrated mass and energy balances based on experimental results and assessing the overall economic viability of the system. Finally, TKE, along with project partners, should have conducted a preliminary design study for an upscaled plant. This task should have identified key barriers to scaling up the technology and assess its readiness level (TRL) for commercialization. These efforts, collectively, aimed to support the transition from experimental research to real-world application, ensuring the viability and sustainability of the developed technologies.

We performed a techno-economic assessment of high-temperature direct air capture integrated with Fischer–Tropsch synthesis for jet fuel production. See the figure below. Based on the modelling framework five different design configurations, all with a jet fuel production of more than 25 t/h, were analysed to compare different options for the calcination, the electrolysis and the reverse water gas shift (RWGS) processes. As a part of the technical evaluation, it is found that up to 78 % of the captured CO_2 can be converted to CO in the calciner highlighting the potential to intensify the process by facilitating both the calcination and the RWGS processes in a single component. The kinetics of the reactions taking place in the calciner are not addressed in this analysis, and it is essential to verify them under the specified conditions outlined in this study. In general, the carbon capture efficiency is above 50 % which indicates that most of the captured carbon ends up in the jet fuel; however, there is still a potential to increase it further by recirculating more of the lights and waxes. In terms of heat integration, the heat recovery potential is greatest in the system configurations based on solid oxide electrolysis (SOEC) with up to 85 % heat recovery compared to about 30 % in the alkaline-electrolysis based systems. Overall, the energy efficiency of the different system configurations ranges from 30.6 % to 39.0 % with the highest efficiency achieved by the system configuration based on SOEC, electrically heated calcination and no RWGS reactor. The fuel specific energy consumption, in this case, is given by 122 MJ/kg Jet fuel in which the DAC energy consumption constitutes 16 % of the total energy demand. The different system configurations are also compared from an economic point of view using NPV analysis to determine the minimum fuel selling price (MFSP). The obtained MFSP values range from 4.45 to 6.32 EUR/L which is significantly higher than existing estimates in literature. Monte Carlo analysis was implemented to account for uncertainties in cost parameters such as discount rate, electricity and heat prices and equipment costs. This analysis indicates that the MFSP is highly sensitive towards changes in the cost parameters and that the potential MFSP might be significantly lower than the initial conservative estimate suggests. This highlights the need for detailed cost considerations when evaluating the economic feasibility of future e-fuels along with the necessity of producing components significantly cheaper than the initial estimations in this paper. Among the configurations studied, alkaline electrolysis conbined with electrical calcination, and no RWGS reactor, achieves the lowest MFSP, indicating that the cost-intensive capital requirements associated with SOEC outweigh the gains in energy efficiency. Moreover, the need for the development of an economically viable electrically heated calciner capable of handling high-temperature hydrogen is emphasized. In general, reducing the levelised cost of hydrogen (LCOH) is crucial for enhancing the economic viability of the process, as it is

the primary driver of the high MFSP. Specifically, the breakeven LCOH, given by an NPV of zero, ranges from 1.4 to 2.1 EUR/kgH2 with the potential of a significant increase if more optimistic cost estimates can be applied. Lastly, maximizing jet fuel yield emerges as a key factor for the future potential of this process. In conclusion, this paper highlights the potential advantages of integrating a hydrogen-based calcination atmosphere with a high-temperature DAC system generating syngas for jet fuel production while demonstrating that the electrolysis required for fuel production is the primary driver of electricity demand and system cost.

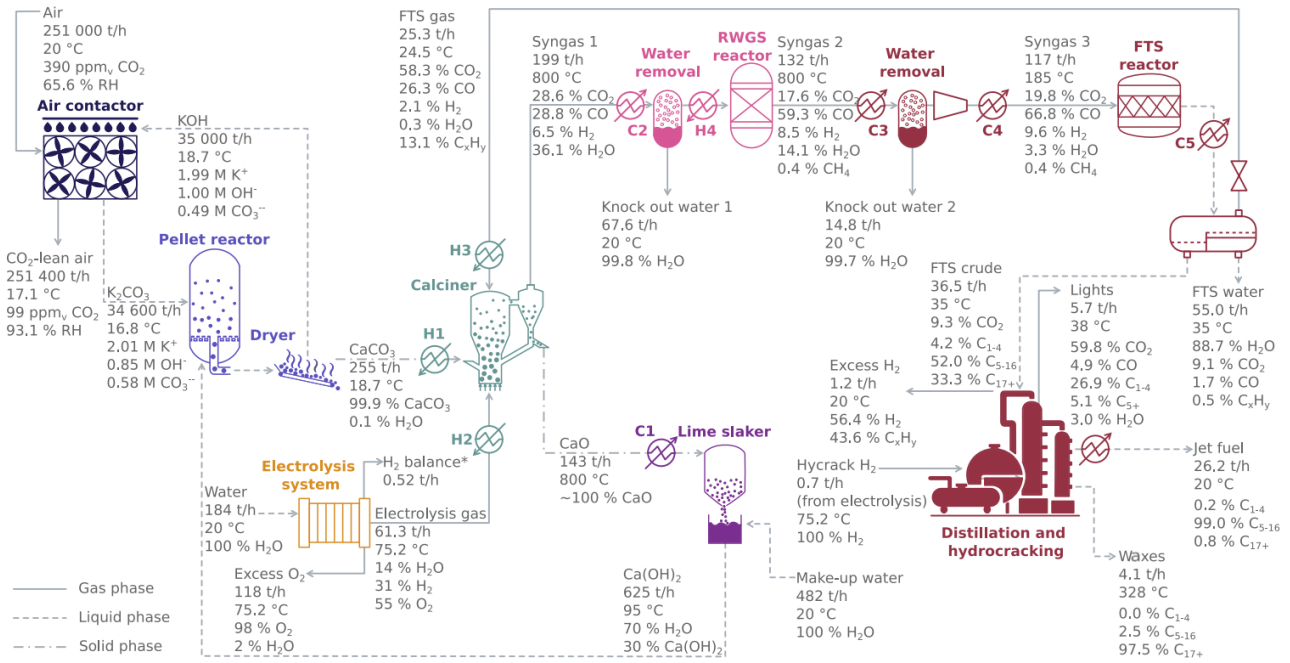

Figure 2 Process flow diagram of the combined DACCU process including results for the Base case (AEC) depicting the stream compositions, stream temperatures and an indication of the state of the streams. All percentages are given as mass fractions unless otherwise stated.

Utilisation of project results

The project has highlighted many new risks of the original design, but also fostered many new ideas on how overcome technical and economical challenges. First of all, for liquid based DAC systems, efforts should be directed towards more efficient or radically new regeneration methods. Specifically for systems incorporating a calcium-looping, development and demonstration of an electric calciner is paramount. However, new methods for regenerating the liquid sorbent directly should also be explored. Furthermore, we will further explore new DAC integration pathways. This project, specifically, looked at FT based fuels. But integration of DAC with the production of other carbon containing fuels and chemicals should also be investigation. The project results will also be used to development a new DAC technology, different from what was proposed in this project, which has the potential to significantly lower the levelized cost CO2 captured from the atmosphere.

5. Project conclusion and perspective

Following are the conclusions of the project:

- The project successfully evaluated a high-temperature Direct Air Capture (DAC) system integrated with Fischer-Tropsch synthesis for jet fuel production.
- It found that up to 78% of the captured CO_2 could be converted to CO in the calciner, showing strong potential for process intensification.
- Carbon capture efficiency was generally above 50%, with room for improvement through better recirculation of light fractions and waxes.
- Solid oxide electrolysis cell (SOEC) systems showed the highest heat recovery potential (85%) compared to alkaline electrolysis-based systems (30%).
- Economic analysis revealed a minimum fuel selling price (MFSP) of 4.45 to 6.32 EUR/L, significantly higher than previous estimates, but with potential reductions through cost optimization.
- The cost of electrolysis was identified as the primary driver of electricity demand and system cost.
- The need for an electrically heated calciner capable of handling high-temperature hydrogen was emphasized.
- Reducing the levelized cost of hydrogen (LCOH) was highlighted as a crucial factor for economic feasibility.

Following are the anticipated next steps:

- Further assessment and validation of reaction kinetics in the calciner to ensure process efficiency.
- Exploration of new DAC integration pathways beyond jet fuel, such as other carbon-based fuels and chemicals.
- Development and demonstration of an electrically heated calciner for calcium-looping systems.
- Investigation of alternative methods for liquid sorbent regeneration to improve DAC efficiency.
- More detailed economic modeling to refine cost estimates and optimize system design.
- A preliminary design study for an upscaled plant to identify scalability challenges and readiness for commercialization.

Following are the impacts on future development:

- DAC is expected to play a crucial role in the green transition by providing a nearly unlimited source of CO_2 for Power-to-X (PtX) applications.
- Atmospheric CO_2 capture will be essential for achieving carbon neutrality by 2050, especially for hard-to-decarbonize industries.
- The project highlights the potential of DAC despite its higher costs compared to point-source CO_2 capture, reinforcing the need for technological advancements.

- Results suggest that DAC could become a dominant source of industrial CO_2, with projections indicating 80% of CO_2 for industrial use coming from the air in the long term.
- Future research based on this project could lead to a more cost-effective DAC system, potentially transforming the economics of CO_2 capture and utilization.

6. Appendices

- Add link to relevant documents, publications, home pages etc.