Closing the Carbon Cycle in Plasma-Based CO_2 Splitting – A Techno-Economic Perspective

Samuel Jaro Kaufmann, Paul Rößner* and Kai Peter Birke

DOI: 10.1002/cite.202400143

This techno-economic analysis examines the impact of CO_2 capture energy and capital costs on plasma-based power-to-liquid (PtL) systems, identifying strategies to minimize the net production costs (NPC) for synthetic fuels. Three future development scenarios were defined. One, focusing on high efficiencies, reaches NPC of 2.9 EUR L^{-1} of marine diesel. The approach of prioritizing high CO_2 conversion results in costs of 3.7 EUR L^{-1}. A more balanced approach between efficiency and conversion achieves an NPC of 2.6 EUR L^{-1}. Further NPC reductions are possible by sourcing lower-cost renewable electricity, reducing the NPC further to a minimum of 1.6 EUR L^{-1}. These findings underscore that direct air capture (DAC) cost-efficiency and process integration improvements are essential for scalable, economically viable CO_2 utilization in PtL processes.

Keywords: CO_2 capture, CO_2 splitting, Direct air capture, Plasma, Techno-economics

Received: October 31, 2024; *revised:* March 14, 2025; *accepted:* March 19, 2025

1 Introduction

The efficient closing of the technical carbon cycle is currently one of the most important issues surrounding the energy transition. Looking at CO_2 emissions and climate goals both globally and nationally, simply reducing emissions from technical processes is no longer sufficient. For example, Seithümmer et al. consider the CO_2 budget, which shows that CO_2 targets can only be achieved by exponentially reducing sectoral emissions. It is necessary to actively extract CO_2 from exhaust gases and the environment using renewable energy and convert it into higher-value products such as fuels or chemicals [1–3].

The extraction of CO_2 and subsequent conversion can take place using power-to-X technologies. For a complete process chain, a CO_2 capture process is required, which can be operated with both electrical energy and thermal energy. In addition, CO_2 must be utilized, e.g., by splitting it into CO and O_2. Alternatively, it is also possible to carry out the reaction by supplying co-reactants such as methane or hydrogen. Together with a hydrogen supply, for example by using water electrolysis, synthetic fuel can finally be produced, e.g., kerosene, diesel or petrol in the Fischer-Tropsch synthesis, but methanol can also be synthesized with the CO/H_2 mix [4, 5].

Plasma processes are a promising option for CO_2 utilization in power-to-X, as they can be efficiently connected to renewable electricity due to their operating conditions and flexibility. The fast response time of these electrified processes makes them perfect for fluctuating electricity production with renewable energies. In addition, warm plasma technologies like gliding arc or microwave plasma can operate at temperature regions between 500 and 2000 °C that allow efficient heat integration with heat demanding processes, reducing the energy input compared to Joule heating. If plasma-based CO_2 splitting and similar processes such as plasma-based dry reforming of methane are further developed, they have a high potential in terms of energy efficiency due to vibrational excitation of molecules by electron collisions [6–8].

To classify and compare the potential of new processes, techno-economic analyses (TEA) are one method often applied. Based on modeling that highlights interactions with other plant components, the profitability of a process can be estimated and development levers can be identified. With regard to power-to-X and power-to-liquid (PtL), TEAs are already available for many technologies, which expect costs of 2.0–2.9 EUR L^{-1} for the year 2050, depending on the boundary conditions and above all on electricity costs. The prerequisite here is successful upscaling and establishment in an industrial environment [5, 9].

---

[1] Samuel Jaro Kaufmann,
[1] Dr. Paul Rößner (paul.roessner@ipv.uni-stuttgart.de),
[1] Prof. Dr.-Ing. Kai Peter Birke
[1] University of Stuttgart, Institute for Photovoltaics, Electrical Energy Storage systems, Pfaffenwaldring 47, 70569 Stuttgart, Germany.

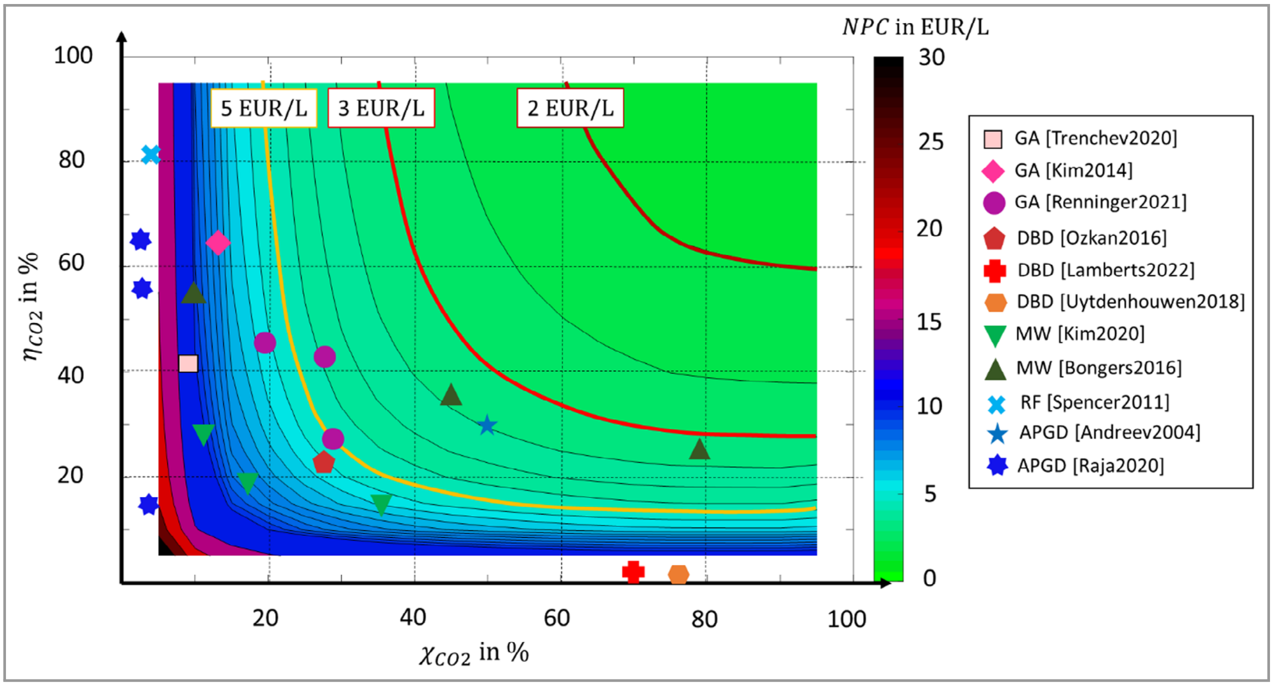

Figure 1. Techno-economic potential over CO_2 conversion and plasma efficiency including oxygen separation with mixed ionic electronic conductors and gas diffusion electrodes [11, 12]; inclusion of plasma performances in gliding arc (GA) [13–15], dielectric barrier discharge (DBD) [16–18], microwave plasma (MW) [19, 20], radio frequency plasma (RF) [21], atm. pressure gliding arc (APGD) [22, 23].

In previous papers, we analyzed the techno-economics of plasma-based CO_2 capture in PtL plants. In one of the two studies, the capture of CO_2 from the exhaust gas stream of a cement plant was assumed. Based on this assumption, the operating costs for CO_2 supply corresponded to 60 EUR/t_{CO2}, which was taken from a study carried out by Roussanaly et al. [10]. Based on this, net production costs between 8.5 and 3.5 EUR L^{-1} were achieved in selected scenarios. Based on a variation of the plasma parameters, the techno-economic potential around 2.4 EUR L^{-1} was specified. In a further study, the overall process was optimized by integrating a calcium looping process in which waste heat from the plasma is used to release CO_2 via the calcination reaction. In this way, both the CO_2 supply and the recycle were considered. Through this optimization, in the scenario net production costs of 2.5 EUR L^{-1} of marine diesel could be achieved. Furthermore, with additional development, a theoretical minimum less than 2 EUR L^{-1} would be possible [11, 12].

Fig. 1 illustrates the techno-economic potential of plasma-based CO_2 splitting in PtL plants. In addition, the performance data of various scientific studies are marked in the diagram. The markers represent different plasma technologies, such as gliding arc (GA), dielectric barrier discharge (DBD), microwave discharge plasma (MW), radiofrequency plasma (RF) and atmospheric pressure glow discharge plasma (APGD). The parameters χ_{CO2} and η_{CO2} are calculated according to Snoeckx et al. [7]. Adding the CO_2 splitting reactors in a PtL plant, leads, in combination with oxygen removal, electrolysers, and Fischer-Tropsch synthesis, to the shown net production costs (NPC) of marine diesel.

The lines in the diagram represent NPC levels of the desired product. The lines show 0.5 EUR L^{-1} steps and the limits of 5, 3, and 2 EUR L^{-1} are highlighted. The classification of plasma processes in terms of efficiency and conversion could also be applied to other CO_2 splitting processes.

The process technology adaptation presented by Seithümmer et al. [24] and analyzed by Kaufmann et al. [12], achieving the NPC reduction to 2.5 EUR L^{-1}, utilizes waste heat from the plasma reactor to carry out carbon recycling with calcium, which significantly improves the techno-economic potential (TEP) indicated in Fig. 1. The question arises as to which influence CO_2 cycling technologies generally have in the PtL process with plasma-based CO_2 splitting. In the study on plasma-based calcium looping also the energy and capital costs of direct air capture (DAC) technologies are summarized. Looking at related literature, there is a wide range in terms of both energy and economics. Depending on the technology readiness levels (TRLs), the energy requirement varies between 1 GJ/t_{CO2} and 10 GJ/t_{CO2} and the capital costs between 60 EUR/t^{y}_{CO2} and 10, 000 EUR/t^{y}_{CO2} [12, 25].

The aim of this work is to show which influence the efficiency and capital costs for CO_2 capture processes have on the PtL process. A plasma reactor for CO_2 splitting and water electrolysis for H_2 production are used for syngas generation in order to produce Fischer-Tropsch marine diesel. By integrating generic CO_2 capture processes, limit values for specific energy and capital costs can be determined for most profitable results. This variation is done for both CO_2 supply for the general input, with main focus on DAC technology, and integrated into the process for CO_2 recycle. The study presented thus serves as an important extension of the techno-economic analyses already published and can also be applied independently to set development targets for the integration of carbon capture technologies in PtL plants.

2 Methodology

Fig. 2 displays a simplified block flow chart of the modeled process. The block shown as input gas CO_2 capture is a generic block of CO_2 capture, which is modeled according to specific energy consumption and specific capital costs. The same applies for the two further CO_2 capture blocks for process gas and flue gas. In addition to the new blocks, further components of a PtL model are used, which correspond to the modeling of previous publications [11, 12]. These components include the plasma reactor for splitting CO_2 and water electrolysis for splitting H_2O. To produce syngas, oxygen is separated using two different technologies, i.e., mixed ionic electronic conductors (MIEC) and gas diffusion electrodes (GDE). This is followed by the synthesis of hydrocarbons via Fischer-Tropsch synthesis (FTS) and product preparation (PP) including residual gas management (RGM).

Effective conversions are increased via recycling streams. Included in the model but not shown in the block diagram are elements of the peripherals, which comprise compressors, heat exchangers, pumps, phase separators, columns, burners, and turbines.

The methodology used is based on the procedure presented by Albrecht et al. for assessing the economic viability of PtL plants [9]. Based on this, a model was created in MATLAB Simulink, which was presented in the previous publications by Kaufmann et al. [11, 12]. The resulting values are the process efficiency (η_{PtL}) and the net production costs (NPC) of the product. In this case, the product is marine diesel, the same as considered in Fig. 1.

$$\eta_{\mathrm{PtL}} = \frac{\dot{m}_{\mathrm{product}} \cdot \mathrm{LHV}_{\mathrm{product}}}{P_{\mathrm{e,tot}}} \tag{1}$$

$$\mathrm{NPC} = \frac{\mathrm{ACC} + \mathrm{OPEX}_{\mathrm{direct}} + \mathrm{OPEX}_{\mathrm{indirect}} + \mathrm{ALC}}{\dot{m}_{\mathrm{product}} \cdot t_{\mathrm{operation}}} \tag{2}$$

In addition to these variables, the power requirement of CO_2 capturing and the capital expenditures $\mathrm{CAPEX}_{\mathrm{CO2C}}$ are also considered and these variables are related to the total values P_{tot} and CAPEX. The boundary conditions correspond to the previous papers by Kaufmann et al. This adoption provides better comparability and allows us to focus on the influences of CO_2 capturing.

The calculation of CAPEX via cost functions, CEPCI (chemical engineering plant cost index) values, and factors for installation etc. was carried out according to previous papers [11, 12].

On the one hand, the study aims to analyze the influence of the specific energy and capital costs for CO_2 supply via DAC on the techno-economy. The parameter range of variation orientates on the mentioned literature data and is from $e_{\mathrm{spec}} = 0.5\frac{\mathrm{GJ}}{\mathrm{t_{CO2}}} \ldots 10\frac{\mathrm{GJ}}{\mathrm{t_{CO2}}}$ and $c_{\mathrm{spec,CAPEX}} = 60\frac{\mathrm{EUR}}{\mathrm{t}^{\mathrm{y}}_{\mathrm{CO2}}} \ldots 10,000\frac{\mathrm{EUR}}{\mathrm{t}^{\mathrm{y}}_{\mathrm{CO2}}}$.

On the other hand, the inclusion of CO_2 capture processes to recycle unconverted CO_2 at two different plant positions is investigated with a variation of $e_{\mathrm{spec}} = 0.05\frac{\mathrm{GJ}}{\mathrm{t_{CO2}}} \ldots 1.65\frac{\mathrm{GJ}}{\mathrm{t_{CO2}}}$ and $c_{\mathrm{spec,CAPEX}} = 50\frac{\mathrm{EUR}}{\mathrm{t}^{\mathrm{y}}_{\mathrm{CO2}}} \ldots 1,650\frac{\mathrm{EUR}}{\mathrm{t}^{\mathrm{y}}_{\mathrm{CO2}}}$. Besides the variation of energy and capital costs the amount of CO_2 which gets extracted is also varied. For this the parameter $x_{\mathrm{CO2,out,\ CO2C}}$ is used, which regulates the output CO_2 concentration of the process on a certain value.

The variations were investigated in different future scenarios. Three scenarios were defined for this purpose, which represent different further developments of the performance of plasma-based CO_2 splitting up to the

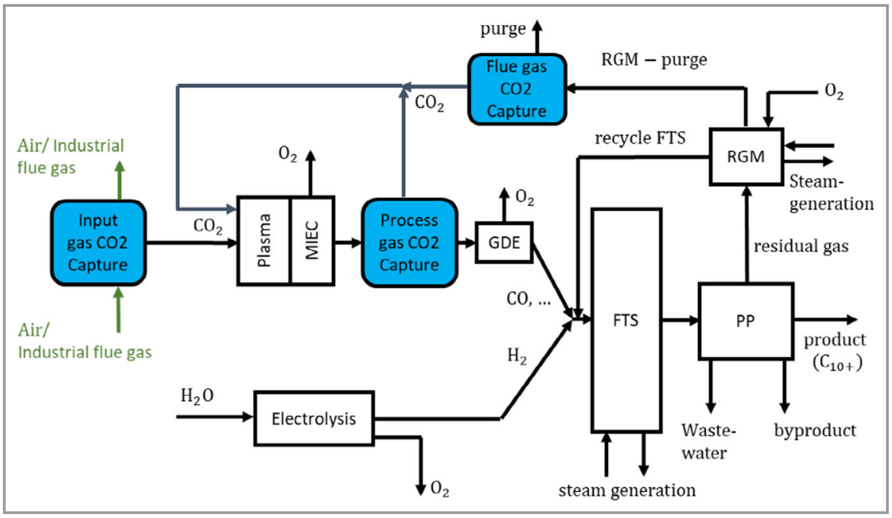

Figure 2. Block flow scheme of important components of the modeled process with the components: input gas CO_2 capture, plasma reactor, mixed ionic electronic conductors (MIEC), process gas CO_2 capture, gas diffusion electrode (GDE), electrolysis, Fischer-Tropsch synthesis (FTS), product preparation (PP), residual gas management (RGM), and flue gas CO_2 capture.

year 2050. Scenario SB (scenario balance) comprises a balanced development towards an efficiency of 50 % with a conversion of 45 %. This development could be achieved with GA, MW or APGD plasma technologies, see Fig. 1. Scenario SE (scenario efficiency) and SC (scenario conversion) present unilateral developments in efficiency and conversion and are defined by 80 % efficiency at 20 % conversion and 20 % efficiency at 80 % conversion. The development focusing on efficiency probably will be more likely achieved with GA and RF technologies, the development focusing on conversion with MW or APGD. The theoretical maximum of the efficiency was calculated in a study of Berthelot et al. to 87 % [26]. Because of the current technology readiness level of the plasma-based CO_2 splitting, it is justifiable to assume further optimizations in performance. For example, in the chemical industry, processes like Haber-Bosch doubled their energy efficiency from first plants to modern state-of-the-art plants.

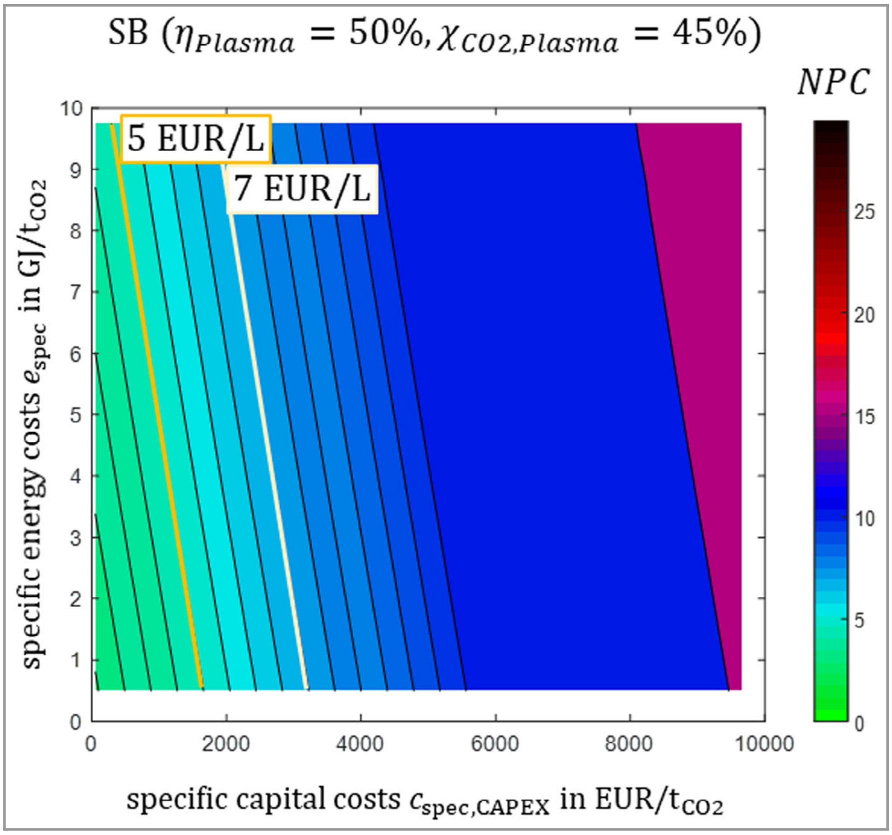

Figure 3. Net production costs (NPC) plotted over the specific energy costs and specific capital costs of the input gas CO_2 capture, in this case a generic direct air capture technology; plasma performance of scenario SB.

3 Results and Discussion

In this chapter the simulation results are presented and discussed. This includes a comparison with results of the processes presented in the previous papers.

3.1 Scenarios

The three scenarios without DAC and without process included CO_2 recycling are considered as benchmark. In the map of the techno-economic potential already shown in Fig. 1, it is assumed that CO_2 is supplied via a point source and that specific costs of $e_{spec} = 0.4\ \frac{GJ}{t_{CO2}}$ and $c_{spec} = 100\ \frac{EUR_{CAPEX}}{t^{y}_{CO2}}$ are present. The boundary conditions were selected so that the necessary energy requirements and capital costs correspond to the requirements for the monoethanolamine (MEA) scrubbing of cement plant exhaust gas [10]. In the scenarios, this leads to net production costs of 3.0 EUR L^{-1} (SB), 5.0 EUR L^{-1} (SE), and 3.7 EUR L^{-1} (SC). These NPC include a share of 4–5 % due to the capital costs of the CO_2 supply. The overall process efficiency η_{PtL} varies between 27 % (SB), 21 % (SE), and 17 % (SC). The production costs NPC_{SC} are lower than NPC_{SE} despite the poorer η_{PtL}, as the capital costs of other components such as the FTS, the GDE, and the peripherals are significantly lower at $NPC_{SC,ACC} = 0.7$ EUR L^{-1} compared to $NPC_{SE,ACC} = 1.9$ EUR L^{-1}.

3.2 Influence of Direct Air Capture Development

In order to achieve a certain degree of location independence and to reduce CO_2 from the atmosphere in general, the idea of using direct air capture (DAC) processes is also being considered. However, as already shown in the previous chapter, the energy requirements and capital costs of DACs are highly variable depending on the technological readiness level (TRL) of the DAC technology. In Fig. 3, the NPC are plotted over the specific energy and capital costs of the DAC for scenario SB. Figs. A.1a and b in the Appendix display the same variations for the SE and SC scenarios.

High specific capital costs $c_{spec,CAPEX}$ of the DAC can impede the profitability of the overall process. It can be clearly seen that profitability suffers greatly once increasing the specific capital costs. Accordingly, the further development of DAC technologies towards lower CAPEX is one of the most important challenges. Energy costs have less influence but should still be kept as low as possible to achieve

Table 1. Dimension of a direct air capture (DAC) at different CO_2 mass flows and concentrations.

DAC dimensions	1000 kg_{CO2}/h (8000 t_{CO2}/y)	30, 000 kg_{CO2}/h (240,000 t_{CO2}/y)	150,000 kg_CO2/h (1,200,000 t_CO2/y)
400 ppm to 300 ppm	$h = 1.4$ m, $A = 930$ m^2 CAPEX = 19 Mio. EUR	$h = 1.4$ m, $A = 2.8e4$ m^2 CAPEX = 560 Mio. EUR	$h = 1.4$ m, $A = 6.9e4$ m^2 CAPEX = 2, 500 Mio. EUR
400 ppm to 200 ppm	$h = 3.4$ m, $A = 465$ m^2 CAPEX = 17 Mio. EUR	$h = 3.4$ m, $A = 1.4e4$ m^2 CAPEX = 500 Mio. EUR	$h = 3.4$ m, $A = 6.9e4$ m^2 CAPEX = 2, 500 Mio. EUR
400 ppm to 100 ppm	$h = 6.7$ m, $A = 310$ m^2 CAPEX = 18 Mio. EUR	$h = 6.7$ m, $A = 0.9e4$ m^2 CAPEX = 540 Mio. EUR	$h = 6.7$ m, $A = 4.6e4$ m^2 CAPEX = 2, 700 Mio. EUR

acceptable NPC values. It should be noted here that heat coupling can also be employed. In the three scenarios, the potentially usable heat loss in the plasma reactor over the year is 1375 TJ (SB), 310 TJ (SE), and 1145 TJ (SC). In relation to the annual CO_2 demand of 593 000 t_{CO2} (SB), 1 177 000 t_{CO2} (SE), and 228 000 t_{CO2} (SC), this energy demand would be covered for SB up to $e_{spec} = 2.3 \frac{GJ}{t_{CO2}}$, for SE up to $e_{spec} = 0.26 \frac{GJ}{t_{CO2}}$, and for SC up to $e_{spec} = 5 \frac{GJ}{t_{CO2}}$.

A comparison of the three scenarios demonstrates that the increase in NPC is lowest in the SC scenario, which significantly reduces the influence of energy and capital costs. In the balanced scenario SB, a minimum of 3 EUR L^{-1} can be achieved with an efficient, favorable DAC. If efficiency decreases, the costs for a favorable technology increase to a maximum of 4.5 EUR L^{-1} (at 10 GJ/t_{CO2}). In the case of the efficiency-heavy plasma scenario SE, this dependency is significantly greater. While a minimum of 5 EUR L^{-1} can be achieved, an increased energy requirement leads to an increase in costs to > 10 EUR L^{-1}. With an efficient technology, however, the limit of 7 EUR L^{-1} is already exceeded at 800 EUR/t^{y}_{CO2} and the 10 EUR L^{-1} limit at 2000 EUR/t^{y}_{CO2}.

A case study was also carried out in which the dimensioning of a DAC was performed using an absorption counterflow system. Using the boundary conditions of common systems, the dimensions were summarized in Tab. 1 by varying the CO_2 mass and the outlet concentration. The stated height h describes the column height with the packing used. The DAC size can be varied by stacking the individual columns. The area A describes the total column base area, which determines the number of columns depending on the individual diameter. In the CAPEX shown, an individual diameter of 5 m was assumed as well as other boundary conditions from Kaufmann et al. [12]. The specific CAPEX resulting from the dimensioning varies between $c_{spec,CAPEX} = 2080 \frac{EUR}{t^{y}_{CO2}}$ and $2400 \frac{EUR}{t^{y}_{CO2}}$, depending on the scaling and absorption height. It must be considered that the cost functions of thin-walled columns were used here, which fulfil the stability requirements but can also be replaced by more cost-effective alternatives.

An interesting approach to the more cost-viable design of a DAC system is, for example, the retrofitting of decommissioned power plant infrastructures, especially cooling towers [27]. This approach is a good way of reducing the CAPEX of a DAC. However, it leads to a certain degree of location lock-in.

3.3 Influence of Recycling Carbon through a Process Gas CO_2 Capture

As already observed in Sect. 3.1, the use of the SC scenario leads to lower NPC than the SE scenario due to the smaller dimensions of other plant components. In order to achieve both higher PtL efficiency and product yield as well as reduced CAPEX, the process gas CO_2 capture is integrated into the overall plant. Fig. 4 shows the NPC via the outlet concentration after the CO_2 capture component.

In the case of efficiency-heavy development in SE, the integration of the process gas CO_2 capture helps to improve profitability as long as the capital costs are $c_{spec,CAPEX} \leq 650 \frac{EUR}{t^{y}_{CO2}}$. In scenario SB, in which the lowest NPC can be achieved, this improvement also applies. However, the extent of the influence varies. While an improvement of ΔNPC of up to 2 EUR L^{-1} can be achieved for SE with favorable CO_2 capture capital costs, this range is only just below 0.5 EUR L^{-1} for SB. The optimum is therefore just below 2.5 EUR L^{-1}. The reduction of the NPC in SE results in a decrease in FTS and peripheral dimensioning, which leads to an increased product yield and raises the PtL efficiency from 21 % to 30 %. In the case of scenario SC, integration leads to a deterioration in economic efficiency, as the additional CAPEX has a greater impact than the reduction in the dimensioning of the remaining components.

The same variation was also carried out for the flue gas CO_2 capture positioned at the end of the process. However, as there is no cost reduction in any variation in the case of this process variation, no plot is shown here. Although its use results in a reduction in the externally required CO_2 input, the benefit is offset by the CAPEX of the CO_2 capture. In addition, there is no reduction in the component dimensioning of FTS, GDE, or the periphery as a result, which means that this type of carbon cycle only has advantages from an ecological point of view.

Looking again at a case study in which the CAPEX of a counter current absorption CO_2 capture is analyzed, the process gas version has the advantage that the concentration gradient is significantly higher and, therefore, a significantly larger CO_2 mass can be absorbed over a certain height.

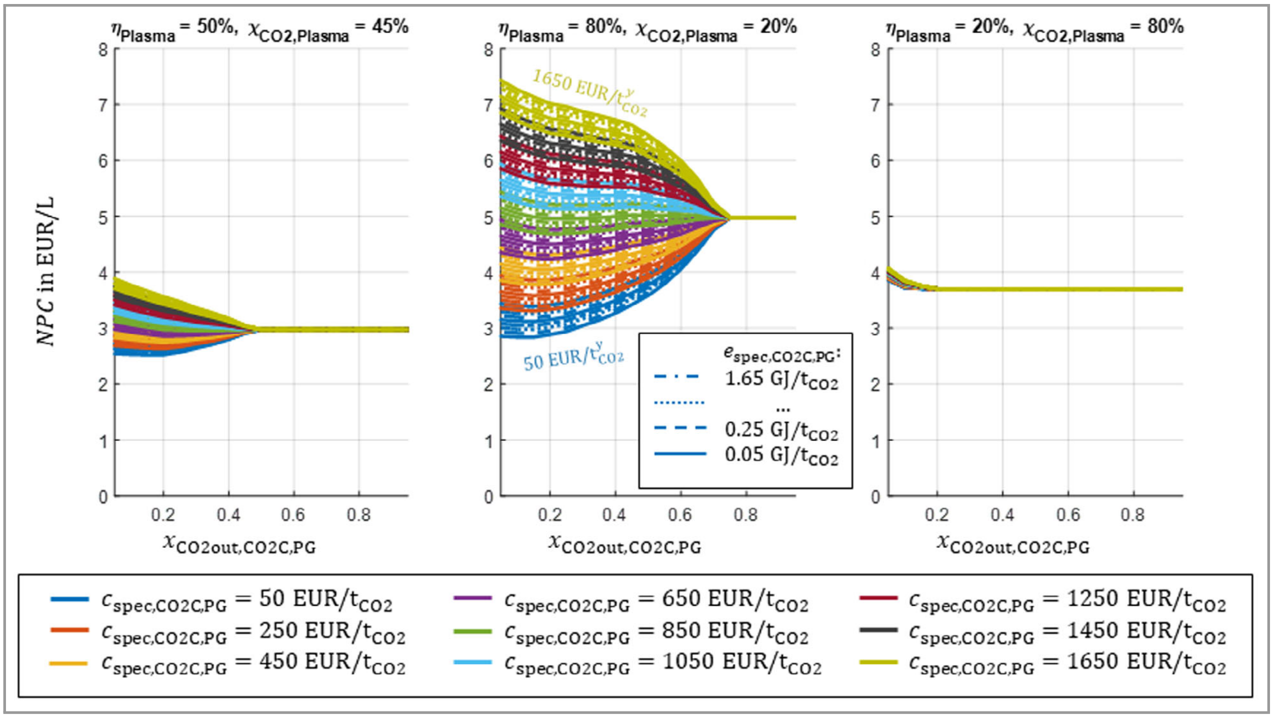

Figure 4. Net production costs plotted over the output concentration of CO_2 in the process gas CO_2 capture; scenario SB (left), scenario SE (mid), and scenario SC (right).

Tab. 2 presents various dimensions. Compared to the DAC, the parameters of the filling change, which increases the performance at higher CO_2 concentrations. The same column cost functions were used as in Tab. 1.

It is noticeable that a significantly smaller column volume is required to achieve the desired effect of CO_2 absorption. In contrast to the DAC, a considerably greater height is necessary due to the concentration height and a distinctly smaller surface area, as significantly more CO_2 can be absorbed along the column. As with the DAC, the height h and the area A are only the individual column height and the total column area, and the system can still be scaled to relatively flexible dimensions using stack and gas management.

If the specific CAPEX is determined on the basis of the values shown, it varies between 0.3 EUR/t_{CO2} for the SE scenario and 2 EUR/t_{CO2} for SC. However, it must be taken into account here that this only relates to the extraction of CO_2 and not yet to its recycling. Therefore, this assumption only works if the regeneration of the bound CO_2 takes place in a converted part of the plant, ideally the plasma reactor. If a separate apparatus is required, a similarly dimensioned regeneration column will probably be necessary and the CAPEX will at least double. However, as the specific CAPEX is very low anyway, this does not make the biggest difference. If, although the factor method for piping etc. has already been applied, further costs arise, the difference to the CAPEX of DAC technologies is still immense.

4 Conclusion

This study analyzed the influence of specific energy and capital costs of carbon capture technologies on the techno-economics of plasma-based production of synthetic fuels.

Table 2. Dimension of a process gas CO_2 capture at different CO_2 mass flows and concentrations.

DAC dimensions	1000 kg_{gas}/h (550 . . . 6100 t_{CO2}/y)	30, 000 kg_{gas}/h (16,500 . . . 184,000 t_{CO2}/y)	150, 000 kg_{gas}/h (83,000 . . . 920,000 t_{CO2}/y)
80% to 10% (SE)	$h = 43$ m, $A = 0.01$ m^2 CAPEX = 0.0018 Mio. EUR	$h = 43\ m,\ A = 0.26\ m^2$ CAPEX = 0.06 Mio. EUR	$h = 43\ m,\ A = 1.32\ m^2$ CAPEX = 0.3 Mio. EUR
55% to 10% (SB)	$h = 39$ m, $A = 0.01$ m^2 CAPEX = 0.0019 Mio. EUR	$h = 39\ m,\ A = 0.26\ m^2$ CAPEX = 0.05 Mio. EUR	$h = 39\ m,\ A = 1.32\ m^2$ CAPEX = 0.27 Mio. EUR
20% to 10% (SC)	$h = 18.3$ m, $A = 0.01$ m^2 CAPEX = 0.001 Mio. EUR	$h = 18.3\ m,\ A = 0.26\ m^2$ CAPEX = 0.03 Mio. EUR	$h = 18.3\ m,\ A = 1.32\ m^2$ CAPEX = 0.16 Mio. EUR

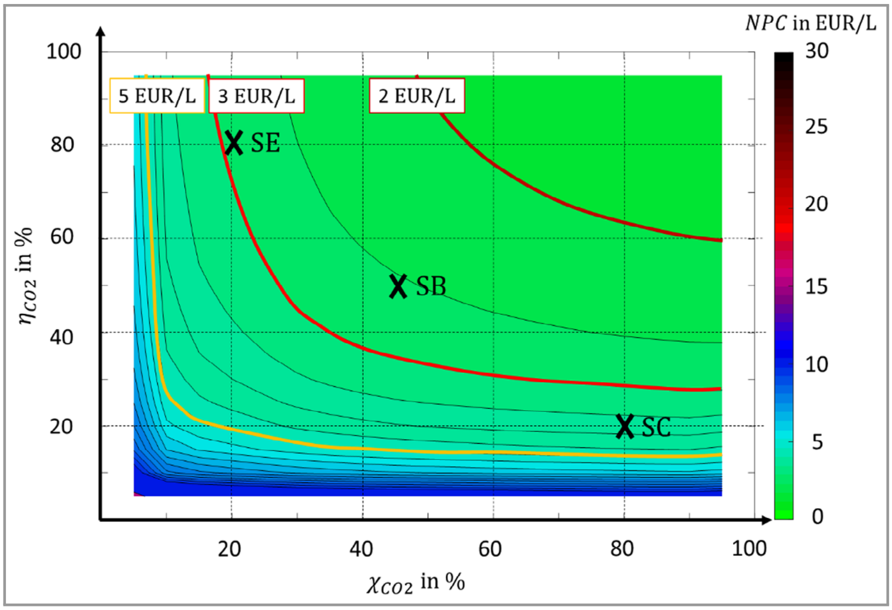

Figure 5. Optimized techno-economic potential of plasma-based CO_2 splitting with the process gas CO_2. Plot of the net production costs NPC over conversion χ_{CO2} and efficiency η_{CO2}. Marked scenario values SB (scenario balance), SE (scenario efficiency), and SC (scenario conversion).

The wide range of data on the energy consumption of technologies for direct air capturing of CO_2 and subsequent supply as process feed has an immense influence on the profitability of the entire PtL process. While energy consumption of approx. $0.1\frac{\mathrm{GJ}}{\mathrm{t_{CO2}}}$ is available when using technologies for capturing CO_2 from point sources, this fluctuates between 0.5 and $10\frac{\mathrm{GJ}}{\mathrm{t_{CO2}}}$ for DAC technologies. This deviation leads to a divergence of $\Delta\mathrm{NPC} = \pm\ 2\ \mathrm{EUR\ L^{-1}}$ in the plasma scenario under consideration with a balanced efficiency/conversion ratio. Fluctuating specific capital costs have an even greater impact on production costs. The fluctuations found in the literature between $100\frac{\mathrm{EUR}}{\mathrm{t^{y}_{CO2}}}$ and $10,000\frac{\mathrm{EUR}}{\mathrm{t^{y}_{CO2}}}$ lead to a deviation of $\Delta\mathrm{NPC} = \pm\ 10\ \mathrm{EUR\ L^{-1}}$. However, it must be noted here that the high specific CAPEX above $2000\frac{\mathrm{EUR}}{\mathrm{t_{CO2}}}$ is attributable to a technology that is still at a low TRL. A fluctuation of $1000\frac{\mathrm{EUR}}{\mathrm{t_{CO2}}}$ already leads to a change of $\Delta\mathrm{NPC} = \pm\ 15\ \mathrm{EUR\ L^{-1}}$. It is therefore an important step towards profitability to reduce the capital costs of DAC technologies. One approach would be to retrofit unused old power plant infrastructure such as large cooling towers.

Based on further investigations, it can be said that the integration of a CO_2 capture for recycling to the plasma reactor can bring significant improvements in plasma reactors focusing on efficiency instead of conversion. If the plasma reactor is based on an efficient reactor with $\eta_{\mathrm{CO2}} =$ 80 % and the conversion is kept at 20 %, the NPC can be improved by up to $\Delta\mathrm{NPC} = \pm\ 2.5\ \mathrm{EUR\ L^{-1}}$ by integrating a process gas CO_2 capture. The introduction of a flue gas CO_2 capture does not prove to be profitable from an economic point of view, only from an ecological point of view.

If the process gas CO_2 capture investigated in Sect. 3.2 with $x_{\mathrm{CO2out,CO2C,\ PG}} = 0.1$ is used as process optimization, the changed graph of the techno-economic potential, shown in Fig. 5, changes so that the 3 EUR $\mathrm{L^{-1}}$ limit is already achieved with conversions of less than 20 % at high plasma reactor efficiencies.

Compared to the plasma-based calcium looping process presented in [12], this study does not focus on the heat losses of the plasma process, which also shifts the map of the techno-economic potential. Assuming 100 $\mathrm{EUR/t^{y}_{CO2}}$ and the utilization of waste heat from the plasma reactor to cover the energy demand, the potential is significantly improved in the area of high efficiencies. The figure shows the TEP with literature data on plasma-based CO_2 splitting, which is identical to Fig. 1. The three scenarios discussed are optimized to 2.6 EUR $\mathrm{L^{-1}}$ (SB), 2.9 EUR $\mathrm{L^{-1}}$ (SE), and 3.7 EUR $\mathrm{L^{-1}}$ (SC).

Heat integration is an important issue and is considered in the conducted modeling. Excess heat from the plasma process is used to fulfil the demand of CO_2 capture and downstream FTS. However, it should be noted that, depending on the plasma technology, other temperature levels are also achieved, which must correspond to those of CO_2 capture technology in terms of temperature gradients.

In the illustration of the TEP of Fig. 5, a point source was employed as the CO_2 supply for better comparison to Fig. 1. If a DAC is used instead of the point source, the NPC increases. The amount of increase is depicted in Fig. 6, for the scenario SB with conversion 45 % and efficiency 50 %.

If the CAPEX increases by 200 $\mathrm{EUR/t^{y}_{CO2}}$, the NPC rises by 0.25 EUR $\mathrm{L^{-1}}$. In order to stay below the limit of 3 EUR $\mathrm{L^{-1}}$, the DAC technology in the optimized process should not cost more than 500 $\mathrm{EUR/t^{y}_{CO2}}$ in CAPEX.

The variations carried out are all based on the boundary condition of $c_{\mathrm{electricity}} = 55\frac{\mathrm{EUR}}{\mathrm{MWh}}$, which was already used in [12] for the future scenario 2050. As the share of electricity costs represents a large proportion of the total costs, this is an important lever for further reducing the NPC. Assuming a direct coupling of renewable energies, these could be reduced to a value of 25 EUR $\mathrm{MWh^{-1}}$ according to [28]. In relation to the TEP shown in Fig. 5, this leads to a further reduction in the NPC in the individual scenarios to the values 1.6 EUR $\mathrm{L^{-1}}$ (SB), 1.9 EUR $\mathrm{L^{-1}}$ (SE), and 2.0 EUR $\mathrm{L^{-1}}$ (SC).

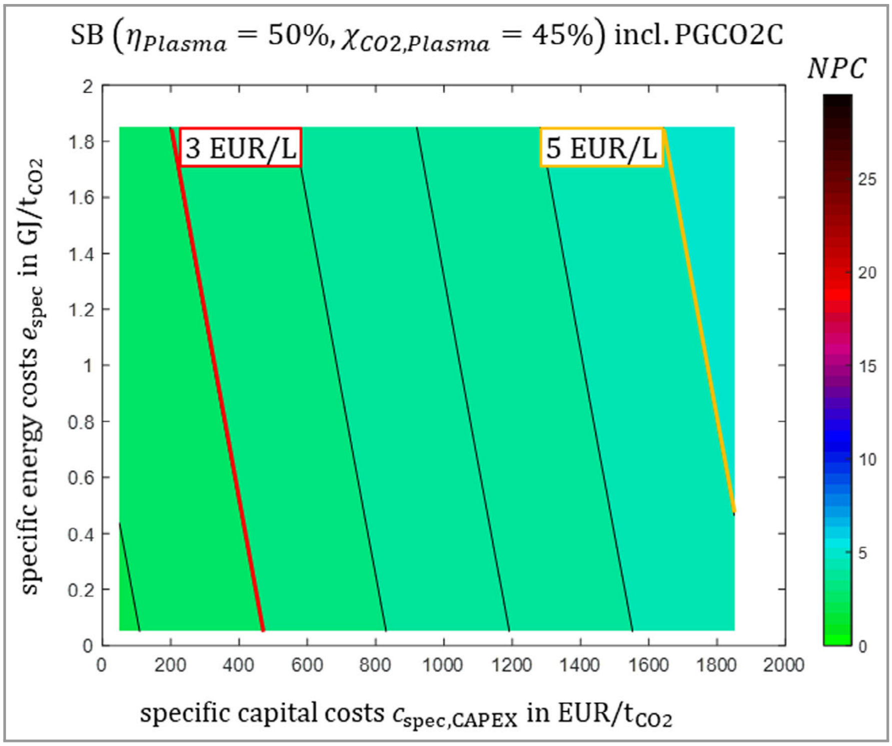

Figure 6. Net production costs plotted over the specific energy costs and specific capital costs of the input gas CO_2 capture, in this case a generic direct air capture technology

In conclusion, it can be stated that the integration of a CO_2 capture in the process is highly profitable for plants with medium to low CO_2 conversion. In addition, the further development of DAC technologies should focus on reducing specific CAPEX. An even more profitable process chain can be achieved, if costs of the electricity are lower.

Data can be provided upon request.

Acknowledgment

This research was part of the project BlueFire, which was funded by the Vector Stiftung with the grant number P2021-0113. The authors would like to thank the founder, the university, the institute, and friends and family for daily support.

Open access funding enabled and organized by Projekt DEAL.

Appendix A

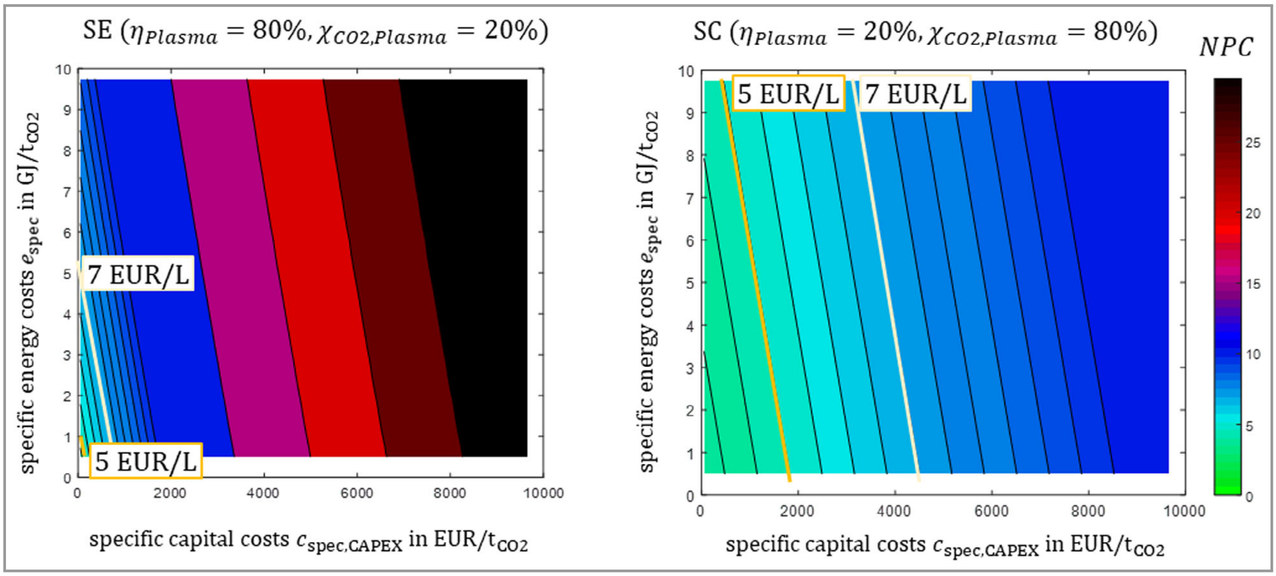

Figure A1. Net production costs (NPC) plotted over the specific energy costs and specific capital costs of the input gas CO_2 capture, in this case a generic direct air capture technology; plasma performance of scenario SE and SC.

Symbols used

Greek letters

χ	[%]	conversion
η	[%]	efficiency

Abbreviations

ACC	annual capital costs
ALC	annual labor costs
APGD	atmospheric pressure glow discharge
CAPEX	capital expenditures
DAC	direct air capture
DBD	dielectric barrier discharge
FTS	Fischer-Tropsch synthesis
GA	gliding arc
GDE	gas diffusion electrode
LHV	lower heating value
MEA	monoethanolamine
MIEC	mixed ionic electronic conductors
MW	microwave
NPC	net production costs
OPEX	operational
PtL	power-to-liquid
PP	product preparation
RF	radio frequency
RGM	residual gas management
SB	scenario balance
SC	scenario conversion
SE	scenario efficiency
TEA	techno-economic analysis
TEP	techno-economic potential
TRL	technological readiness level

References

[1] https://iea.blob.core.windows.net/assets/830fe099-5530-48f2-a7c1-11f35d510983/WorldEnergyOutlook2022.pdf (Accessed on July 22, 2024)

[2] *"Sektorkopplung" - Untersuchungen und Überlegungen zur Entwicklung eines integrierten Energiesystems* (Eds.: H.-M. Henning, F. Ausfelder, F. Drake, B. Erlach, M. Fischedick, C. Kost, W. Münch, K. Pittel, C. Rehtanz, J. Sauer, K. Schätzler, C. Stephanos, M. Themann, E. Umbach, K. Wagemann, H. Wagner, U. Wagner), Acatech, München **2024**. DOI: https://doi.org/10.24406/publica-fhg-298843

[3] V. B. Seithümmer, J. V. Lutz, S. J. Kaufmann, H. Chinnaraj, P. Rößner, K. P. Birke, *Energy Adv.* **2024**, *3*, 2887–2895. DOI: https://doi.org/10.1039/D4YA00246F

[4] J. van de Loosdrecht, F. G. Botes, I. M. Ciobica, A. Ferreira, P. Gibson, D. J. Moodley, A. M. Saib, J. L. Visagie, C. J. Weststrate, J. W. Niemantsverdriet, in *Comprehensive Inorganic Chemistry II* (Eds.: J. Reedijk, K. R. Poeppelmeier), Elsevier, Amsterdam **2013**.

[5] https://www.concawe.eu/wp-content/uploads/Rpt_22-17.pdf (Accessed on July 22, 2024)

[6] A. Bogaerts, X. Tu, J. C. Whitehead, G. Centi, L. Lefferts, O. Guaitella, F. Azzolina-Jury, H.-H. Kim, A. B. Murphy, W. F. Schneider, T. Nozaki, J. C. Hicks, A. Rousseau, F. Thevenet, A. Khacef, M. Carreon, *J. Phys. D: Appl. Phys.* **2020**, *53* (*44*), 443001. DOI: https://doi.org/10.1088/1361-6463/ab9048

[7] R. Snoeckx, A. Bogaerts, *Chem. Soc. Rev.* **2017**, *46* (*19*), 5805–5863. DOI: https://doi.org/10.1039/c6cs00066e

[8] *Plasma Catalysis* (Eds.: X. Tu, J. C. Whitehead, T. Nozaki), Vol. *106*, Springer International Publishing, Cham **2019**.

[9] F. G. Albrecht, D. H. König, N. Baucks, R.-U. Dietrich, *Fuel* **2017**, *194*, 511–526. DOI: https://doi.org/10.1016/j.fuel.2016.12.003

[10] S. Roussanaly, C. Fu, M. Voldsund, R. Anantharaman, M. Spinelli, M. Romano, *Energy Procedia* **2017**, *114*, 6229–6239. DOI: https://doi.org/10.1016/j.egypro.2017.03.1761

[11] S. J. Kaufmann, P. Rößner, S. Renninger, M. Lambarth, M. Raab, J. Stein, V. Seithümmer, K. P. Birke, *Appl. Sci.* **2023**, *13* (*8*), 4839. DOI: https://doi.org/10.3390/app13084839

[12] S. J. Kaufmann, F. Bender, P. Rößner, S. Renninger, J. Stein, V. Seithümmer, H. Chinnaraj, K. P. Birke, *J. CO2 Util.* **2024**, *85*, 102892. DOI: https://doi.org/10.1016/j.jcou.2024.102892

[13] G. Trenchev, A. Bogaerts, *J. CO2 Util.* **2020**, *39*, 101152. DOI: https://doi.org/10.1016/j.jcou.2020.03.002

[14] S. C. Kim, M. S. Lim, Y. N. Chun, *Plasma Chem. Plasma Process.* **2014**, *34* (*1*), 125–143. DOI: https://doi.org/10.1007/s11090-013-9499-8

[15] S. Renninger, P. Rößner, J. Stein, M. Lambarth, K. P. Birke, *Processes* **2021**, *9* (*11*), 2063. DOI: https://doi.org/10.3390/pr9112063

[16] A. Ozkan, A. Bogaerts, F. Reniers, *J. Phys. D: Appl. Phys.* **2017**, *50* (8), 84004. DOI: https://doi.org/10.1088/1361-6463/aa562c

[17] H. Lamberts-Van Assche, G. Thomassen, T. Compernolle, *J. CO2 Util.* **2022**, *64*, 102156. DOI: https://doi.org/10.1016/j.jcou.2022.102156

[18] Y. Uytdenhouwen, S. van Alphen, I. Michielsen, V. Meynen, P. Cool, A. Bogaerts, *Chem. Eng. J.* **2018**, *348*, 557–568. DOI: https://doi.org/10.1016/j.cej.2018.04.210

[19] H. Kim, S. Song, C. P. Tom, F. Xie, *J. CO2 Util.* **2020**, *37*, 240–247. DOI: https://doi.org/10.1016/j.jcou.2019.12.011

[20] W. Bongers, H. Bouwmeester, B. Wolf, F. Peeters, S. Welzel, D. van den Bekerom, N. den Harder, A. Goede, M. Graswinckel, P. W. Groen, J. Kopecki, M. Leins, G. van Rooij, A. Schulz, M. Walker, R. van de Sanden, *Plasma Processes Polym.* **2017**, *14* (6), 1600126. DOI: https://doi.org/10.1002/ppap.201600126

[21] L. F. Spencer, A. D. Gallimore, *Plasma Chem. Plasma Process.* **2011**, *31* (*1*), 79–89. DOI: https://doi.org/10.1007/s11090-010-9273-0

[22] S. N. Andreev, V. V. Zakharov, V. N. Ochkin, S. Y. Savinov, *Spectrochim. Acta, Part A* **2004**, *60* (*14*), 3361–3369. DOI: https://doi.org/10.1016/j.saa.2004.01.034

[23] B. Raja, R. Sarathi, R. Vinu, *Energy Technol.* **2020**, *8* (*12*). DOI: https://doi.org/10.1002/ente.202000535

[24] P. Rößner, S. J. Kaufmann, V. Seithümmer, *Conf. on CO$_2$-based Fuels and Chemicals*, Universität Stuttgart, April **2023**. DOI: https://doi.org/10.13140/RG.2.2.21044.63367

[25] M. Erans, E. S. Sanz-Pérez, D. P. Hanak, Z. Clulow, D. M. Reiner, G. A. Mutch, *Energy Environ. Sci.* **2022**, *15* (*4*), 1360–1405. DOI: https://doi.org/10.1039/D1EE03523A

[26] A. Berthelot, A. Bogaerts, *J. CO2 Util.* **2018**, *24*, 479–499. DOI: https://doi.org/10.1016/j.jcou.2018.02.011

[27] R. Sager, K. Tosuner, N. Petersen, M. Wirsum, *Waste heat from fuel synthesis integrated into retrofitted DAC plants* **2024**.

[28] A. Christensen, *ICCT, Assessment of hydrogen production costs from electrolysis: United States and Europe* **2020**.