PROCEEDINGS OF ECOS 2026 - THE 39TH INTERNATIONAL CONFERENCE ON

EFFICIENCY, COST, OPTIMIZATION, SIMULATION AND ENVIRONMENTAL IMPACT OF ENERGY SYSTEMS

28 JUNE – 03 JULY, 2026, CONSTANTA, ROMANIA

Estimating the value of biogenic carbon dioxide in Power-to-X value chains

***Jenna Ruokonen*[a]*, Petteri Laaksonen*[b]*, Tero Tynjälä*[c] *and Niko Kinnunen*[d]**

[a] *LUT University, Lappeenranta, Finland, jenna.ruokonen@lut.fi, CA*
[b] *LUT University, Lappeenranta, Finland, petteri.laaksonen@lut.fi,*
[c] *LUT University, Lappeenranta, Finland, tero.tynjala@lut.fi,*
[d] *LUT University, Lappeenranta, Finland, niko.kinnunen@lut.fi*

Abstract:

Carbonaceous, fossil-free electricity-based fuels, chemicals, and other derived products depend on sustainable carbon sources, such as biogenic CO_2 from industrial point sources. Techno-economic analyses of e-fuel and e-chemical production have consistently reported higher production costs in comparison to their fossil-based counterparts. Prior studies have justifiably emphasised the price of renewable electricity in e-hydrogen production due to its dominant contribution to total production costs. Consequently, the pricing of biogenic CO_2 has attracted comparatively limited attention as it has been generally regarded as a less significant cost factor. Moreover, full industrial-scale carbon capture and utilisation have not yet been established for biogenic sources of CO_2, leaving industries without a clear basis for pricing the captured biogenic CO_2. This study examines the effect of CO_2 pricing on the profitability of e-methanol and e-methanol–based e-kerosene production. An economic model is developed for a base case, and a sensitivity analysis is conducted to evaluate how variations in raw material and product prices affect product profit margins. The model yields positive profit margins for both e-methanol and e-kerosene production in the assumed base case. The sensitivity analysis suggests strong dependence between profitability and electricity and product prices, while distinctly positive profit margins can still be retained even when the CO_2 price is 50% above the base value. The findings of this study suggest that biogenic CO_2 may indeed have greater monetary value than previously anticipated based on the range of capture cost estimates. More broadly, e-fuel and e-chemical value chains seem to tolerate higher prices of biogenic CO_2 without suffering from weakened economic viability. These findings may inform strategic decision-making in relation to CO_2 capture investments, market formation for biogenic CO_2, and the negotiation of long-term supply agreements.

Keywords:

Biogenic CO_2; Power-to-X; Pricing; Sensitivity analysis; Value formation.

1. Introduction

The transition from fossil-based to renewable-based industries is central to achieving the targets set to mitigate the effects of climate change. The use of renewable electricity and sustainable sources of carbon via Power-to-X (PtX) technologies provides an important pathway for defossilising hydrocarbon-based processes, including the production of fuels, chemicals, and plastics. However, the cost competitiveness of PtX products remains limited in comparison to conventional fossil-based alternatives, as widely demonstrated in techno-economic analyses [1-5]. Previous studies have emphasised the cost of renewable electricity in e-hydrogen production as it constitutes the largest share of the total production costs of e-hydrogen–based products. By contrast, the pricing of biogenic CO_2 has received considerably less attention, apart from studies addressing the techno-economics of point-source capture configurations [6-8]. In addition, full industrial-scale investments in biogenic CO_2 capture remain scarce, and a mature CO_2 market has yet to emerge. This creates a challenge for producers of biogenic CO_2, such as pulp mills, biomass-fuelled power plants, and biowaste-to-energy facilities, when determining an appropriate price level for captured CO_2.

This study focuses on biogenic point sources of CO_2 as they are effectively the only CO_2 sources, along with direct air capture (DAC), currently eligible for the production of sustainable fuels under the prevailing regulatory frameworks of the European Union (EU). Biogenic CO_2 and e-hydrogen constitute a feedstock that can be converted into e-methanol and e-kerosene through the value chain illustrated in Fig. 1. e-Methanol is selected as the intermediate product examined in this study due to its broad applicability in both the chemical industry and the transport sector. e-Kerosene, in turn, represents a high value-added end product with significant market potential under the EU's ReFuelEU Aviation regulation, which establishes minimum blending mandates for sustainable aviation fuels and includes a dedicated sub-quota for synthetic kerosene [9].

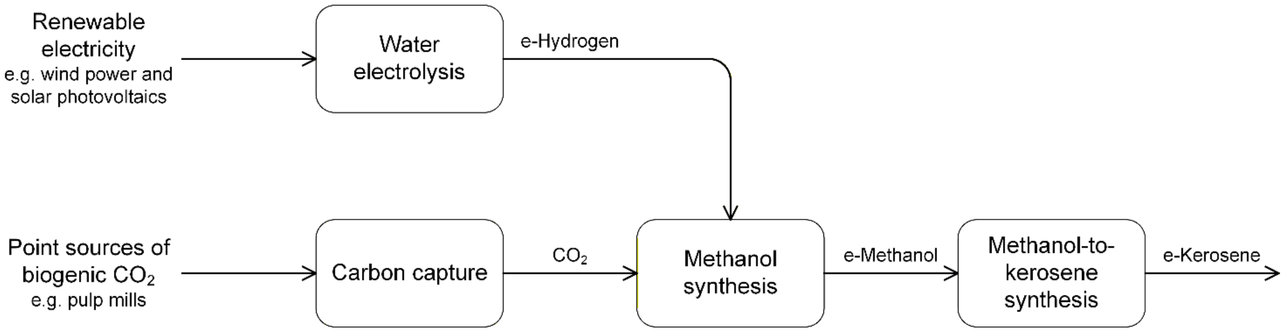


Figure. 1. The Power-to-X value chain considered in this study.

According to Nieminen et al. [1], methanol synthesis based on direct CO_2 hydrogenation comprises four principal process steps. First, the CO_2 and hydrogen feed streams are compressed and heated to reactor conditions. In the second step, the process feed is converted into methanol and by-products, such as water, within a reactor. The third step consists of a train of separation columns and coolers that separate crude methanol from unreacted gases. The crude methanol is then sent to the final process step, while the unreacted gases are recycled to the reactor feed. In the final separation step, by-product water is removed from methanol by distillation, and the methanol is purified through the removal of residual CO_2.

e-Methanol production is followed by e-fuel synthesis that yields e-kerosene as one of the products. As described by Ruokonen et al. [2], the process comprises seven steps. In the first step, methanol is converted into light olefins, mainly ethylene and propylene, as well as by-products, such as water, methane, ethane, and aromatics, via a dimethyl ether intermediate. In the second step, water is separated from the hydrocarbons, and light gases and aromatics are separated from the olefins by distillation. The third step includes an oligomerisation reactor in which light olefins are converted into higher hydrocarbons. Next, the reactor effluent is sent to a distillation train to separate liquified petroleum gas fraction and gasoline-range hydrocarbons from the heavier products. The aromatic fraction obtained in the second step is treated with hydrogen to convert durene into its isomers with lower melting points. The hydroisomerised aromatic fraction is then blended with the gasoline fraction. The heavier fuel fraction, consisting of kerosene and diesel-range hydrocarbons, is also treated with hydrogen to saturate olefinic compounds and thereby improve the fuel's resistance to oxidation. In the final step, kerosene is separated from diesel by distillation.

This study aims to provide insight into the economics of e-methanol and e-kerosene production from the perspective of pricing of biogenic CO_2. This work hypothesises that biogenic CO_2 may be valued higher than is implied by literature-based capture cost estimates. To examine this proposition, an economic model is developed based on techno-economic literature on e-methanol and e-kerosene production. A sensitivity analysis is then conducted using the model to assess the effect of CO_2 price on product profit margins. This approach enables a comparison of relative effect of different price components on the economic performance of e-fuel and e-chemical production.

2. Methodology

The effects of raw material and product pricing on the profit margins of e-methanol and e-methanol–based e-kerosene are examined by means of an economic model. Process simulations and techno-economic analyses reported by Nieminen et al. [1] for e-methanol synthesis and by Ruokonen et al. [2] for e-kerosene production provide the basis for the model developed in this work. Within the model, the profit margins of e-methanol and e-kerosene are calculated from the raw material costs of biogenic CO_2 and hydrogen produced using renewable electricity.

Total production costs c_{tot} are assumed to consist of raw material costs c_r and other costs c_o including capital expenditure, operating expenses other than raw materials, and the cost of capital. This relationship is expressed in Eq. (1). In the case of hydrogen, the raw material cost depends on the specific energy consumption of the electrolysis equipment E_s and the price of renewable electricity p_{el} according to Eq. (2). The e-methanol raw material cost follows Eq. (3), which incorporates the mass fractions of hydrogen w_H and carbon w_C in the methanol molecule, together with the corresponding mass-based conversion efficiencies, $\eta_{MeOH,H}$ and $\eta_{MeOH,C}$. Mass fractions are taken into account in the calculations to consider the value of carbon in CO_2, as the value of oxygen is excluded from the analysis. The conversion efficiencies consider losses of raw materials to by-products and waste streams, which increase both raw material consumption and total production costs. Carbon losses due to coking and catalyst deactivation reactions are excluded from the scope of this analysis. The e-kerosene raw material cost follows the same principle in Eq. (4) but does not consider mass fractions as they are already accounted for in methanol. Finally, the profit margin P of a product is calculated using Eq. (5) by comparing the product price p with its total production cost c_{tot}.

$$c_{i,tot} = c_{i,r} + c_{i,o} = \frac{c_{i,r}}{s_{i,r}} \tag{1}$$

$$c_{H,r} = E_s \cdot p_{el} \tag{2}$$

$$c_{MeOH,r} = c_{MeOH,H} + c_{MeOH,C} = \frac{c_{H,tot} \cdot w_H}{\eta_{MeOH,H}} + \frac{p_{CO2} \cdot w_C}{\eta_{MeOH,C}} \tag{3}$$

$$c_{ker,r} = \frac{c_{MeOH,H}}{\eta_{ker,H}} + \frac{c_{MeOH,C}}{\eta_{ker,C}} \tag{4}$$

$$P_i = \frac{p_i - c_{i,tot}}{p_i} \tag{5}$$

Table 1 summarises the factors and related references used in the model. The table also describes each factor and provides the rationale underlying the selected values. Assumed raw material and product prices are likewise included in the table and are used as base case values in the analysis. The assumed CO_2 and electricity prices reflect price levels often used in relevant techno-economic studies, whereas the e-methanol and e-kerosene prices correspond to their estimated market prices.

Table 1. Factors, values, and references used in the model.

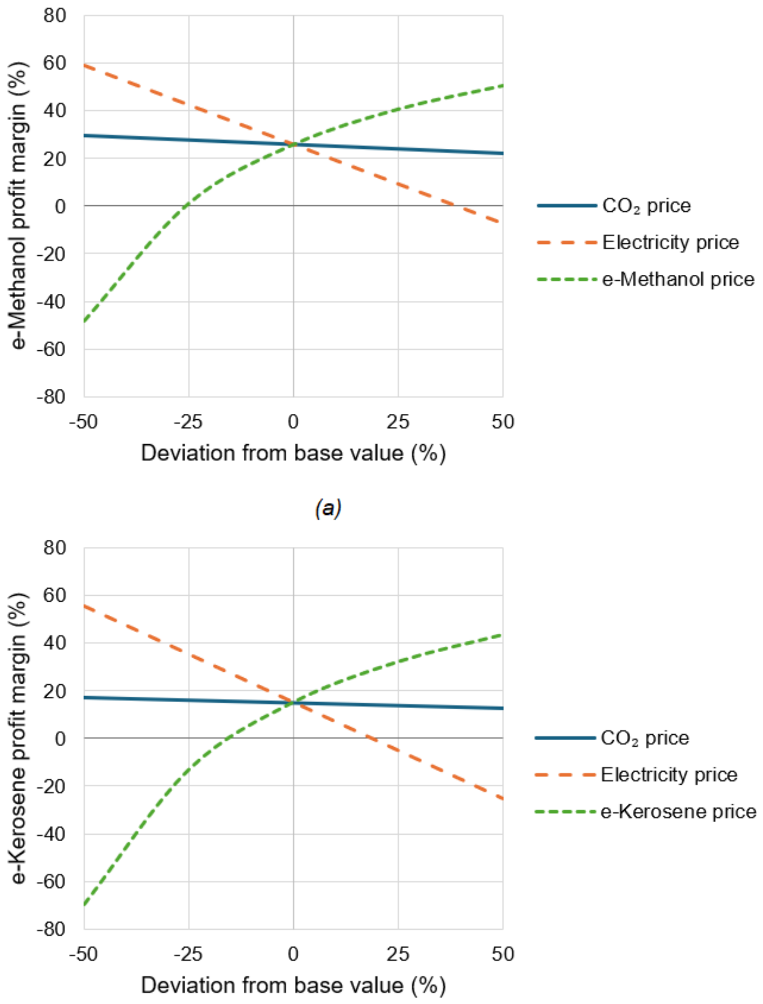
Factor	Symbol	Value	Unit	Reference	Note
Specific energy consumption of electrolysis	E_s	52.5	kWh/kg$_{H2}$	[10]	Average specific energy consumption of alkaline and proton exchange membrane electrolysis
Share of electricity of total production cost of hydrogen	$s_{H,r}$	70	%	[11-13]	Assumed based on the references
Share of raw materials of total production cost of e-methanol	$s_{MeOH,r}$	82	%	[1]	Calculated from the reference
Share of raw materials of total production cost of e-kerosene	$s_{ker,r}$	73	%	[2]	Calculated from the reference
Hydrogen mass fraction in e-methanol	w_H	13	%	[1]	Hydrogen molar mass/methanol molar mass
Carbon mass fraction in e-methanol	w_C	37	%	[1]	Carbon molar mass/methanol molar mass
Hydrogen mass efficiency in e-methanol production	$\eta_{MeOH,H}$	61	%	[1]	Input hydrogen/e-methanol output ratio, calculated from the Aspen Plus simulation model reported in the reference
Carbon mass efficiency in e-methanol production	$\eta_{MeOH,C}$	91	%	[1]	Input carbon/e-methanol output ratio, calculated from the Aspen Plus simulation model reported in the reference
Hydrogen mass efficiency in e-kerosene production	$\eta_{ker,H}$	13	%	[2]	Input hydrogen/e-kerosene output ratio, calculated from the Aspen Plus simulation model reported in the reference
Carbon mass efficiency in e-kerosene production	$\eta_{ker,C}$	27	%	[2]	Input carbon/e-kerosene output ratio, calculated from the Aspen Plus simulation model reported in the reference
Renewable electricity price	p_{el}	35	€/MWh	Assumed	Base case value
Biogenic CO$_2$ price	p_{CO2}	150	€/t	Assumed	Base case value
e-Methanol price	p_{MeOH}	1000	€/t	Assumed	Base case value
e-Kerosene price	p_{ker}	7000	€/t	Assumed	Base case value

The shares of raw materials in the total production costs of e-methanol and e-kerosene, $s_{MeOH,r}$ and $s_{ker,r}$ in Table 1, are determined as follows. Nieminen et al. [1] report that the production of 2.3 t/h of e-methanol requires 3.9 t/h of CO$_2$ and 0.5 t/h of hydrogen. Applying the CO$_2$ price of 50 €/t and the hydrogen price of 3000 €/t assumed by Nieminen et al. yields annual raw material costs of 14 M€, assuming 8000 annual operating hours. The raw material cost per unit of production capacity is then obtained by dividing the annual cost by the e-methanol production rate, resulting in 788 €/t. This raw material cost per tonne of e-methanol corresponds to 82% of the total production cost of 963 €/t reported by Nieminen et al. In an analogous manner, the modelling results of Ruokonen et al. [2] are used to determine the raw material cost per tonne of e-kerosene. According to Ruokonen et al., 3 t/h of e-methanol and 0.01 t/h of hydrogen yield three product fractions – gasoline, kerosene, and diesel – with a combined output of 1.2 t/h. Using the e-methanol price of 963 €/t and the hydrogen price of 3000 €/t, as assumed by Ruokonen et al., the annual raw material costs of e-fuel production amount to 23 M€. The resulting raw material cost per tonne of e-fuels is 2486 €/t, corresponding to 73% of the total production cost of 3409 €/t reported by Ruokonen et al.

After the economic model has been tuned using the base case values listed in Table 1, a sensitivity analysis is conducted to find the effects of raw material and product pricing on the profit margins of e-methanol and e-kerosene production. In the analysis, raw material and product prices are adjusted by ±50% relative to the base case values to provide a sufficiently broad range of variation.

3. Results and discussion

Under the base case assumptions, e-methanol production yields a profit of 260 €/t, whereas e-kerosene production results in a profit of 1057 €/t. These values correspond to profit margins of 26% and 15%, respectively. Fig. 2 presents the results of the sensitivity analysis of the profit margins.



(a)

(b)

Figure. 2. Results of the sensitivity analysis with a ±50% deviation from the base case: a) e-methanol profit margin, b) e-kerosene profit margin.

As shown in Fig. 2, product and electricity prices have the most significant impact on product profit margins, whereas the effect of CO_2 price is nearly negligible. This limited effect is to be expected, given that carbon accounts for only 10% of the raw material costs of e-methanol and 5% of those of e-kerosene in the base case. Fig. 3 illustrates the effect of CO_2 price on profit margins of e-methanol and e-kerosene in greater detail.

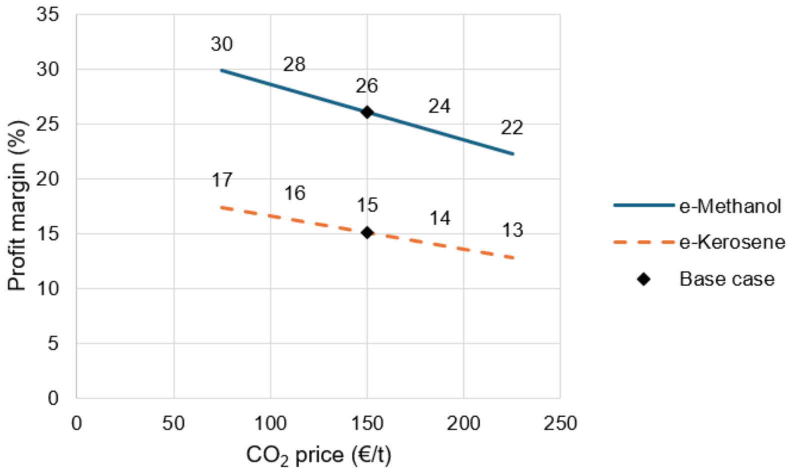


Figure. 3. The effect of CO_2 price on e-methanol and e-kerosene profit margins with a ±50% deviation from the base case.

According to Fig. 3, the CO_2 price has a stronger impact on the profit margin of e-methanol than on that of e-kerosene. The e-methanol profit margin varies by a maximum of 4 percentage points relative to the base value, whereas the e-kerosene profit margin varies by only 2 percentage points. Moreover, the e-kerosene profit margin remains clearly positive even when CO_2 price is 50% higher than the base value, i.e. 225 €/t compared with 150 €/t. This finding indicates that biogenic CO_2 could be priced above 150 €/t without undermining the profitability of e-kerosene production.

In theoretical terms, the price of biogenic point-source CO_2 is bound by the price level of DAC. According to reports from industrial DAC developers, the levelized cost of DAC currently ranges from approximately 500 to 850 €/t [14]. For comparison, the cost of CO_2 captured from pulp mills is estimated at approximately 40–90 €/t excluding storage and transport costs [15]. According to the model developed in this work, a practical upper bound for the CO_2 price would be approximately 660 €/t, assuming that all other prices remain at their base values. At this price level, product profit margins would decline to 0% regardless of the CO_2 source.

A further factor affecting price formation is the demand for e-kerosene created by the ReFuelEU Aviation regulation, which binds both aviation fuel suppliers and aircraft operators. Both suppliers and users of e-kerosene are subject to fines if they fail to comply with the minimum obligations. These fines are specified such that supplying the market with e-kerosene is more cost-effective than paying the fines [9], thereby creating a strong incentive to satisfy the demand generated by the same regulation. The market may therefore become less sensitive to the price of e-kerosene and ultimately to the price of CO_2 when e-kerosene is the end product of the PtX value chain.

Although biogenic CO_2 prices of several hundred euros per tonne, as currently observed for DAC, may be unrealistic, e-methanol and e-kerosene producers appear capable of tolerating higher biogenic CO_2 prices if they can secure renewable electricity at an affordable price and obtain the expected market price for the end products. The ability of the value chain to absorb or pass on the CO_2 cost offers producers of biogenic CO_2 an opportunity to assign a higher value to CO_2 than might otherwise be anticipated, particularly during the early stages of market and value chain formation when demand exceeds supply.

In addition to raw material and product pricing, the carbon efficiency of the CO_2 conversion process also affects overall profitability. As shown in Table 1, CO_2 hydrogenation to e-methanol benefits from a high carbon efficiency of 91%, whereas the efficiency decreases to 27% in the subsequent e-kerosene synthesis due to the broad range of products and by-products formed. The combined carbon efficiency of converting CO_2 to e-kerosene via an e-methanol intermediate is therefore 24%. As discussed above, e-kerosene production appears profitable in the base case at the stated conversion efficiencies. However, the catalysts used in the conversion processes are susceptible to coking and deactivation, which increases costs associated with catalyst regeneration and replacement. Novel catalysts may offer improved stability and selectivity, but this may come at the expense of lower conversion rates. According to the economic model, an overall carbon efficiency as low as 6% would reduce the e-kerosene profit margin to 0%, indicating that a moderate loss in efficiency may be tolerable if accompanied by improvements in other catalyst properties.

4. Conclusions

The aim of this work was to determine whether biogenic CO_2 could be considered more valuable than is generally assumed on the basis of point-source capture costs. The evolution of production costs in a Power-to-X value chain comprising renewable hydrogen production, CO_2 capture from a biogenic point source, e-methanol synthesis, and e-methanol–based e-kerosene production was examined through the development of an economic model. The effects of raw material and product pricing on the profit margins of e-methanol and e-kerosene were assessed by means of a sensitivity analysis. The modelling results demonstrate that renewable electricity and product prices have a substantial effect on the profitability of e-methanol and e-kerosene production, whereas the effect of CO_2 price remains nearly negligible within the same deviation range.

The underdeveloped supply of biogenic CO_2 forms a bottleneck in Power-to-X value chains by increasing risk and uncertainty for downstream investments. The findings of this work indicate that the sensitivity of the value chain to the price of biogenic CO_2 is relatively minor in comparison to other price components. Consequently, a production cost-oriented pricing approach may underestimate the full value of biogenic CO_2 in Power-to-X markets.

The economic model developed in this work appears to yield logically consistent results. The model could be developed further to broaden the scope of value chain analysis, for example, by incorporating point-source CO_2 capture cost factors to determine a potential range of profit margins for a CO_2 capture plant operator. The results reported herein may therefore serve as indicative support for strategic decision-making concerning biogenic CO_2 capture, utilisation and trade.

Nomenclature

Abbreviations

DAC	Direct air capture
EU	European Union
PtX	Power-to-X

Latin symbols

c	cost, €/t
E	energy consumption of electrolysis, kWh/kg$_{H2}$
P	profit, %
p	price, €/t or €/MWh
s	share, %
w	mass fraction

Greek symbols

η	mass efficiency

Subscripts and superscripts

C	carbon
CO_2	carbon dioxide
el	electricity
H	hydrogen
H_2	hydrogen gas
i	component
ker	kerosene
$MeOH$	methanol
o	other
r	raw materials
s	specific
tot	total

References

[1] Nieminen H., Laari A., Koiranen T., CO_2 Hydrogenation to Methanol by a Liquid-Phase Process with Alcoholic Solvents: A Techno-Economic Analysis. Processes 2019;7:405. doi:10.3390/pr7070405. Available at: <https://www.mdpi.com/2227-9717/7/7/405> [accessed 27.3.2026].

[2] Ruokonen J., Nieminen H., Dahiru A.R., Laari A., Koiranen T., Laaksonen P., Vuokila A., Huuhtanen M., Modelling and Cost Estimation for Conversion of Green Methanol to Renewable Liquid Transport Fuels via Olefin Oligomerisation. Processes 2021;9:1046. doi:10.3390/pr9061046. Available at: <https://www.mdpi.com/2227-9717/9/6/1046> [accessed 27.3.2026].

[3] He Y., Song J., Brynolf S., Grahn M., Unlocking decarbonisation in hard-to-abate sectors: A quantile-based comparative techno-economic analysis of e-fuel pathways. Energy Conversion and Management 2026;351:121035. doi:10.1016/j.enconman.2026.121035. Available at: <https://www.sciencedirect.com/science/article/pii/S019689042600004X> [accessed 27.3.2026].

[4] Bellotti D., Rivarolo M., Magistri L., A comparative techno-economic and sensitivity analysis of Power-to-X processes from different energy sources. Energy Conversion and Management 2022;260:115565. doi:10.1016/j.enconman.2022.115565. Available at: <https://www.sciencedirect.com/science/article/abs/pii/S0196890422003612> [accessed 27.3.2026].

[5] Boilley J.-H., Behloul C., Bin Shahrel H., Gürbüz E., Jeandaux C., Khamphasith M., Bellahcene R., Berrady A., Gallucci F., Olivier P., Techno-economic and life cycle assessment of e-kerosene production from captured carbon dioxide and green hydrogen. Energy Conversion and Management 2025;345:120354. doi:10.1016/j.enconman.2025.120354. Available at: <https://www.sciencedirect.com/science/article/abs/pii/S0196890425008787> [accessed 27.3.2026].

[6] Beiron J., Normann F., Johnsson F., A techno-economic assessment of CO_2 capture in biomass and waste-fired combined heat and power plants – A Swedish case study. International Journal of Greenhouse Gas Control 2022;118:103684. doi:10.1016/j.ijggc.2022.103684. Available at: <https://www.sciencedirect.com/science/article/pii/S1750583622001025> [accessed 27.3.2026].

[7] Pérez-Calvo J.-F., Mazzotti M., Techno-economic assessment of post-combustion CO_2 capture using aqueous piperazine at different flue gas compositions and flowrates via a general optimization methodology. International Journal of Greenhouse Gas Control 2022;114:103587. doi:10.1016/j.ijggc.2022.103587. Available at: <https://www.sciencedirect.com/science/article/pii/S1750583622000093> [accessed 27.3.2026].

[8] Salman M., Beguin B., Nyssen T., Léonard G., Techno-economic analysis of AMP/PZ solvent for CO_2 capture in a biomass CHP plant: towards net negative emissions. Frontiers in Energy Research 2024;12:1325212. doi:10.3389/fenrg.2024.1325212. Available at: <https://www.frontiersin.org/journals/energy-research/articles/10.3389/fenrg.2024.1325212/full> [accessed 27.3.2026].

[9] EUROPA – the official web site of the European Union. Regulation (EU) 2023/2405 of the European Parliament and of the Council. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32023R2405> [accessed 27.2.2026].

[10] EUROPA – the official web site of the European Union. Clean Hydrogen JU - SRIA Key Performance Indicators (KPIs). Available at: <https://www.clean-hydrogen.europa.eu/knowledge-management/strategy-map-and-key-performance-indicators/clean-hydrogen-ju-sria-key-performance-indicators-kpis_en> [accessed 27.3.2026].

[11] Zemite L., Jansons L., Kronkalns D., Backurs A., Dzelzitis E., Slutins O., From Electricity Prices to Hydrogen Costs: Evaluating Green Hydrogen Competitiveness Pathways. Latvian Journal of Physics

and Technical Sciences 2026;63(1):51-61. doi:10.2478/lpts-2026-0005. Available at: <https://reference-global.com/article/10.2478/lpts-2026-0005> [accessed 27.3.2026].

[12] Aminaho E.N., Aminaho N.S., Aminaho F., Techno-economic assessments of electrolyzers for hydrogen production. Applied Energy 2025;399:12615. doi:10.1016/j.apenergy.2025.126515. Available at: <https://www.sciencedirect.com/science/article/pii/S0306261925012450> [accessed 27.3.2026].

[13] Roeder T., Rosenstiel A., Monnerie N., Sattler C., Impact of expected cost reduction and lifetime extension of electrolysis stacks on hydrogen production costs. International Journal of Hydrogen Energy 2024;95:1242-1251. doi:10.1016/j.ijhydene.2024.08.015. Available at: <https://www.sciencedirect.com/science/article/pii/S0360319924031641> [accessed 27.3.2026].

[14] Pujal A., Heuckendorff M., Pedersen T.H., Techno-economic analysis of two novel direct air capture-to-urea concepts based on process intensification. Journal of Cleaner Production 2025;496:144932. doi:10.1016/j.jclepro.2025.144932. Available at: <https://www.sciencedirect.com/science/article/pii/S0959652625002823> [accessed 27.3.2026].

[15] Martinez Castilla G., Tumara D., Mountraki A., Letout S., Jaxa-Rozen M., Schmitz A., Ince E., Georgakaki A., Clean Energy Technology Observatory: Carbon Capture, Utilisation and Storage in the European Union - 2024 Status Report on Technology Development, Trends, Value Chains and Markets. Available at: <https://publications.jrc.ec.europa.eu/repository/handle/JRC144142> [accessed 27.3.2026].