Decarbonisation Technology

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The techno-economic metrics of carbon utilisation – Part 2

Explaining the technological and economical parameters of carbon utilisation and how these vary widely depending on external as well as technology-specific variables

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Currently, there is a common misconception that carbon capture, utilisation, and storage (CCUS) means carbon storage (CS) rather than carbon utilisation (CU). The confusion between storage and utilisation is understandable since they both help reduce carbon emissions. The difference between storage and utilisation is that storage involves disposing of waste, whereas utilisation involves efficient use of resources. Since utilisation is more expensive than storage, some utilisation technologies need further development, which explains the current focus on storage.

To help curb carbon emissions, NEDO (New Energy and Industrial Technology Development Organization) entrusted Yokogawa, a leading provider of industrial automation and test and measurement solutions, to perform a strategic decarbonisation study of the Goi industrial area in the Chiba Prefecture at Tokyo Bay, opposite the capital (Yokogawa, 2021). KBC carried out the research related to carbon utilisation for Yokogawa. This research aims to make the industrial area net carbon neutral by 2050, preferably using carbon utilisation rather than storage.

KBC conducted a techno-economic evaluation of the nine carbon utilisation technologies. These technologies and feeds, other than CO_2, are listed in **Table 1**, an abridged version of Table 1 from Part 1.

Part 1 of this two-part article assessed how key variables such as hydrogen requirements, CO_2 utilisation, and product price affect operating costs (KBC, 2022).

Table 2 shows hypothetical price scenarios for green hydrogen and CO_2 utilisation in 2030 and 2050. Whereas the 2030 scenario assumes a high price for green hydrogen and a low price for CO_2 utilisation, the 2050 scenario speculates a much lower price for green hydrogen and a much higher price for CO_2. The primary purpose of this comparison is to demonstrate the sensitivity of the carbon utilisation economics with carbon and green hydrogen pricing.

#	Name	Main product	Non CO_2 feeds
1	Methanation	Methane	H_2
2	Methanol	Methanol	H_2
3	Fischer-Tropsch	Syncrude / SAF	H_2
4	Oxo synthesis	Butanal	Propylene, H_2
5	Carbonation	Building material	Steel slag
6	Xylenes	Mixed xylenes	H_2
7	Urea	Urea	Ammonia (NH_3)
8	Polyols	Polyether carbonate polyol	Propylene oxide (PO)
9	Polymeric carbonates	Polypropylene carbonate (PPC)	Propylene oxide

Table 1 Carbon utilisation technologies

Price estimates for the 2030 and 2050 scenarios have been established with a more rigorous market analysis for the other feeds (propylene, propylene oxide, slag) and the carbon utilisation products. For most feed and product pricing, KBC relied on third-party market intelligence supplied by Argus Media. The investigation concluded that making hydrogen-intensive carbon utilisation technologies available in a scenario depicting high-priced green hydrogen must impose

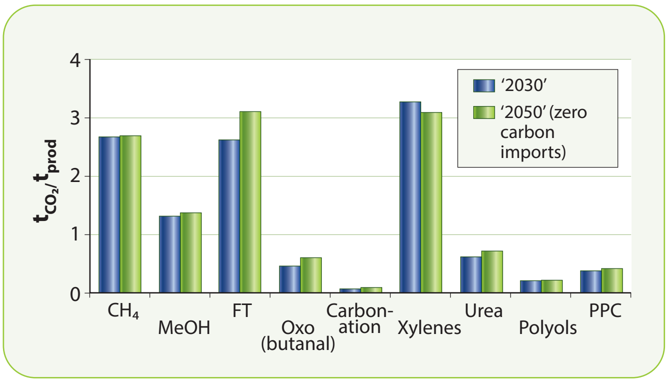

Figure 1 Carbon utilisation intensity (CUI) of the investigated technologies

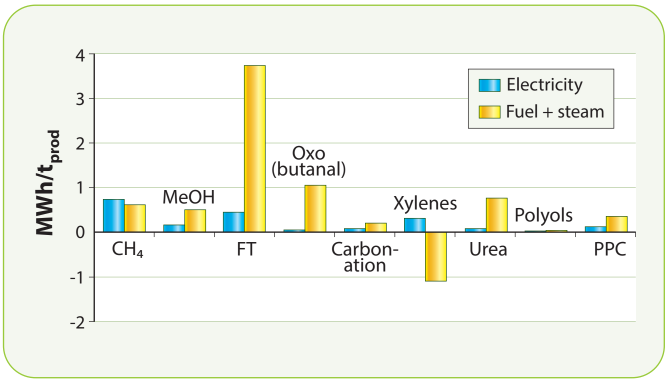

Figure 2 Import of electricity and fuel/steam

either product mandates or high CO_2 prices of USD 350/t.

Part 1 of this article accounted for the carbon impact of imported electricity and fuel and assumed the hydrogen had a zero carbon intensity (CI). **Figure 1** recaptures the carbon utilisation, carbon utilisation intensity (CUI) charts presented for the different technologies. Different power, fuel, and steam emissions factors are assumed for the 2030 and 2050 scenarios illustrated in the bar chart in Figure 1.

Part 2 further develops the techno-economics of carbon utilisation by investigating the impact of the CI of green hydrogen, power, and fuel consumed. The capital expenditure for the different technologies is also compared.

Utility balance: impact of power, fuel, and steam imports on carbon emissions

The carbon utilisation units may import and export electricity as well as steam and/or fuel. However, the balance is primarily determined by the reaction heat, and the heat required for amine regeneration.

Exothermic processes have the potential to use the excess heat for steam generation and export. Synthesis processes using hydrogen tend to be highly exothermic. The methanation, Fischer-Tropsch (FT), and xylenes technologies indeed generate considerable amounts of reaction heat, ranging from 1.8 to 2.9 MWh of product for the xylenes and methane processes, respectively. However, this does not always translate into steam exports. Some technologies use medium-level and high-level heat above 120°C for preheat, while the lower-level heat (<120°C) is lost in cooling. The intermediate-level heat (150-200°C) is often used to produce the necessary steam to regenerate the amine solution, which is used to capture CO_2. Carbon capture is used in the methanation, FT, and Oxo production processes. Capturing and recycling CO_2 are required to avoid large purges of CO_2. However, it requires a significant amount of relatively low-level heat for amine regeneration and electricity for the compression and recycling of captured CO_2.

Ultimately, all technologies are net utility importers except the xylenes process. The xylenes process is a net steam exporter that assumes CO_2 capture is optional, and the best technology available for heat integration has been considered, unlike other technologies studied. In addition, caution should be exercised with respect to the xylenes technology because it is still in its infancy. Consequently, the available yield information was limited. KBC anticipates that further improvements in product selectivity will be achieved once the technology matures.

Figure 2 shows the net import requirements of electricity and fuel/steam, respectively.

The use of import electricity and fuel/steam will lead to emissions that occur outside the carbon utilisation unit. These will be categorised as Scope 1 or Scope 2 emissions depending on whether they occur within a unit located elsewhere on the same production site or

	2030 Scenario	2050 Scenario
Green hydrogen	USD 4000 /t	USD 1500 /t
CO_2 utilisation revenue	USD 50 /t	USD 200 /t

Table 2 Green hydrogen and CO_2 price scenarios based on pre-inflation 2021 prices

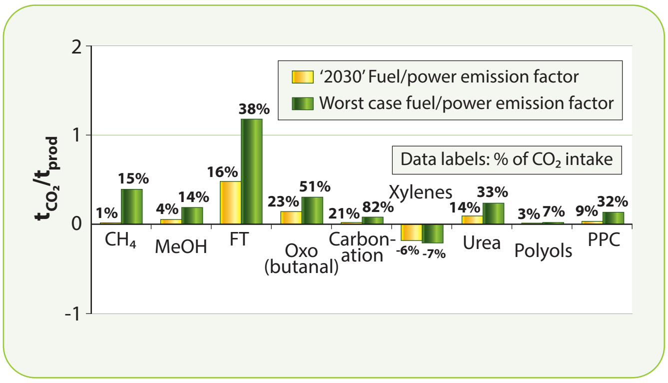

Figure 3 Carbon emissions related to power/fuel imports, $t_{CO2}/ t_{product}$

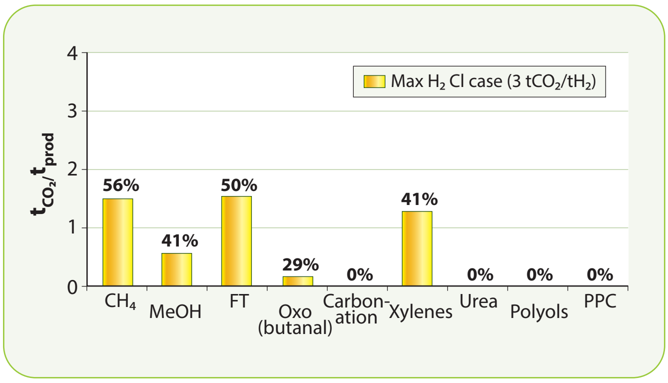

Figure 4 Worst-case carbon emissions related to green hydrogen, $t_{CO2}/ t_{product}$

outside the site. In Figure 1, the utility import-related emissions were subtracted from the CUI, as shown. Note that the hydrogen consumed was assumed to be imported green hydrogen with a zero carbon footprint.

Naturally, emissions related to imported electricity and fuel/steam will depend on their CI. **Table 3** shows the CI of these utilities in the 2030 and 2050 scenarios. It should be noted that the 2030 scenario assumes an initial degree of decarbonisation of the utility imports, whereas the 2050 scenario forecasts total decarbonisation. A worst-case scenario has been considered as a sensitivity case assuming coal is used to produce electricity while heavy residual oil is the imported fuel.

Figure 3 shows the carbon footprint of the utility imports in the 2030 and worst-case scenarios. The data labels show the level of these emissions, expressed as a percentage of the gross carbon intake (i.e. not corrected for the utilities).

In the 2030 scenario, the utility imports offset up to 23% of the carbon intake in the case of Oxo synthesis. If 100 tonnes of CO_2 is sent to the Oxo unit, where it is converted into n-butanal, the steam, power, and fuel intake will generate 23 tonnes of CO_2 outside the Oxo facility. In the worst-case scenario, the offset reaches 82% of the carbon intake for carbonation. The high penalty in the case of carbonation is due to the relatively high use of electricity compared to the CO_2 consumed.

Impact of hydrogen imports on carbon emissions

The CUI chart in **Figure 1** assumes hydrogen imports are carbon-free. The CI of grey hydrogen varies from 8 to 12 t_{CO2}/t_{H2}, depending on the feed type and unit efficiency. **Figure 4** shows the 'max CI case' impact with green hydrogen emitting 3 t_{CO2}/t_{H2}, the upper limit for green hydrogen under the EU taxonomy (Johansen, 2021).

The graph shows that the CI of 'green hydrogen' has a major impact on the CI of hydrogen-intense processes. In the 'max CI case' for methane production, 56% of the carbon intake is offset by the emissions associated with the production of the imported hydrogen. Additionally, the offset exceeds 40% for the methanol, xylenes, and FT synthesis. This means these carbon utilisation technologies will effectively become net CO_2 emitters if fed with grey hydrogen.

Capex

An Association for the Advancement of Cost Engineering (AACE) Class IV, equipment-based, inside battery limits (ISBL) capital cost estimation was done for the nine technologies. **Figure 5** compares the specific investment costs for the different technologies. The low relative costs for some of the technologies are due to simpler processes operating at low temperatures. Processes utilising predominantly gas streams are more capital

	2030 Scenario	2050 Scenario	Worst case
Electricity	0.26	0.00	1.00
Fuel / steam	0.14	0.00	0.28

Table 3 Emission factors including worst case, tCO_2/MWh

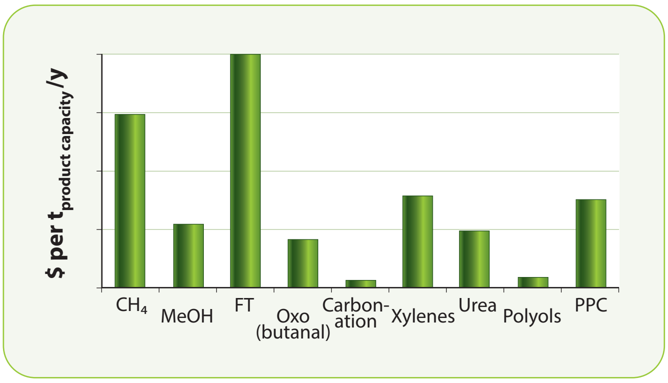

Figure 5 Relative capital cost

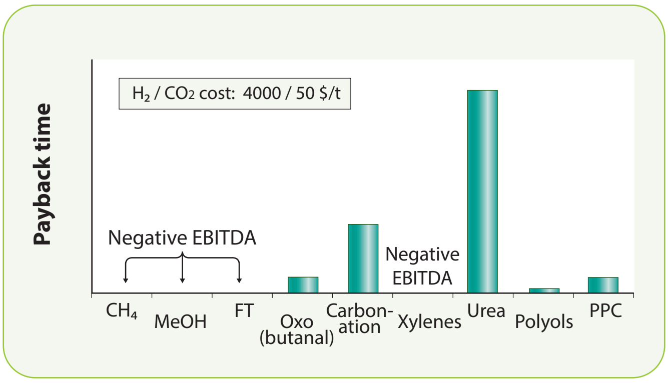

Figure 6 Payback – 2030 scenario

intensive due to either high compression requirements or large equipment sizes if operating at lower pressures.

The additional capital costs will be limited if the carbon utilisation plant is integrated into a much larger existing complex that can provide the utilities needed and has spare offsite and control room facilities. However, adding the outside battery limits (OSBL) costs will be very significant for a remote greenfield project with high import utility requirements.

Overall financial performance

A simple payback time has been calculated as the ratio of the capital cost estimate to the operating revenue/cost balance (see Part 1). Note that the capital cost expressed in 2021 USD is assumed to remain unchanged. The higher the bar in **Figures 6** and **7**, the longer the payback time.

This simplified key performance indicator (KPI) can be used for a preliminary selection of the technologies to consider. A more rigorous financial analysis can then be performed in a future phase.

The payback time is significantly lower in the 2050 scenario with high CO_2 cost and low hydrogen cost than in the 2030 scenario with much lower CO_2 cost and high hydrogen cost. For the technologies that consume no hydrogen (urea, carbonation, polyols, polypropylene carbonate (PPC)), this is largely due to the increased carbon abatement revenue. The graphs also reconfirm that hydrogen cost is the primary economic driver for hydrogen-intensive technologies.

Despite the less appealing 2030 scenario, some of the technologies remain economically attractive due to their limited capital requirements (carbonation, polyols, Oxo) and/or ability to generate high-value products (polypropylene carbonate, Oxo).

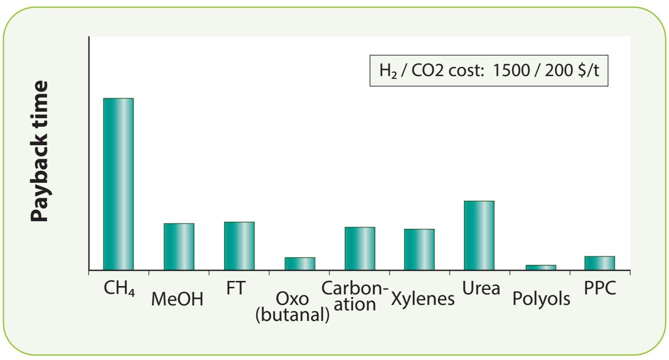

Figure 7 Payback – 2050 scenario

Market size

Table 4 shows the size of the global market demand for each technology considered. Market demand will not be the primary consideration for the size of carbon utilisation unit producing products like methane, methanol, FT, and building materials. However, butanal (Oxo) polyols, and especially polypropylene carbonate, are in much lower

#	Technology	Global product market*
1	Methanation	Large
2	Methanol	Large
3	Fischer-Tropsch	Large
4	Oxo synthesis	Small
5	Carbonation	Large
6	Xylenes	Medium
7	Urea	Large
8	Polyols	Small
9	Polymeric carbonates	Small

* Large: > 100 million t/y, Medium: 10-100 million t/y, Small: <10 million t/y

Table 4 Carbon utilisation product market size

#	Technology	TRL
1	Methanation	8 (IEA, 2021)
2	Methanol	8 (IEA, 2021)
3	Fischer-Tropsch	8 (IEA, 2021)
4	Oxo synthesis	8 (coherentmarketinsights.com, 2022)
5	Carbonation	7-8 (Mooijman, 2021)
6	Xylenes	3 (Nippon Steel, 2020)
7	Urea	9 (Jarvis & Samsatli, 2018)
8	Polyols	8 (World of Chemicals, 2016)
9	Polymeric carbonates	8 (Hubei Sanli Fengxiang, 2022)

Table 5 Technological readiness levels of the technologies

demand worldwide. Producing large quantities of these may lead to surpluses. In light of these technologies offering promising economics, the carbon utilisation potential will be determined primarily by market demand rather than capital costs or earnings before interest, taxes, depreciation, and amortisation (EBITDA).

Technological readiness

A concise description of the different technological readiness levels (TRLs) can be found in another article (Ethakota and Kalpana, 2022). A separate IEA report (IEA, 2021) assessed the TRL for methanation, methanol, and FT at 8 (see **Table 5**).

FT has been applied on an industrial scale since the 1930s but not in combination with the reverse-water-gas-shift step. The same applies to butanal production. Butanal production from CO is a mature technology. However, using CO_2 instead of CO requires a reverse water gas shift step, which is not fully mature, and therefore the TRL of Oxo synthesis production from CO_2 was set at 8 rather than 9. Carbonation is applied on a smaller scale. All the technologies are likely to reach maturity by 2030 except for xylenes synthesis, which is currently only being developed on a lab scale.

Conclusion

The findings of both parts of the CU assessment can be summarised as follows:

- Many carbon utilisation technologies are moving toward technological maturity.
- A large amount of hydrogen is needed to produce fuels and other oxygen-free products, making the technology impractical in the short and medium term due to its high price.
- Sustainable aviation fuel's high value illustrates that production mandates on low CI products can change this equation and make carbon utilisation economically viable at a higher hydrogen cost.
- High-value niche chemicals, especially those containing oxygen, are viable candidates for carbon utilisation. Building materials produced from CO_2 and slag utilise relatively limited amounts of CO_2 but are expected to be economically viable with limited support.
- The CI of the hydrogen consumed is a critical parameter. Even a relatively limited CI will significantly reduce the net CU of hydrogen-intensive technologies. The CI of power and fuel imports can also have a significant impact.

VIEW REFERENCES

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