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Overview of Economic Limits for Converting Waste CO_2 to Fuel in CTL Process

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Abstract: The integration of hydrogen (H_2) into the Coal-to-Liquids (CTL) process offers a promising strategy to convert carbon dioxide (CO_2) emissions into valuable synthetic crude (syncrude), thereby reducing the overall carbon footprint of CTL operations. This study presents a high level economic analysis to determine the maximum cost of H_2 that would make its use in the CTL process financially attractive. The findings demonstrate that access to low-cost electricity for H_2 production can not only boost syncrude yields but also substantially lower CO_2 emissions—especially in regions with abundant renewable energy resources.

Keywords: Carbon Efficiency, Decarbonization of CTL, CO_2 Taxation, Sustainable Energy Systems, Carbon Circularity, Renewable Electricity for Hydrogen Production

1. Introduction

Coal-to-Liquids (CTL) facilities convert coal into liquid fuels; but they are also significant contributors to CO_2 emissions, thereby exacerbating global greenhouse gas concentrations and contributing to climate change challenges [1,2]. As the global energy sector pivots toward more sustainable practices, there is growing interest in leveraging renewable energy resources to reduce the environmental impact of such processes [3]. One promising strategy involves integrating electrolytically produced hydrogen (H_2) into the CTL process, aligning with emerging Power-to-X technologies [4].

Regions with surplus renewable energy—such as wind or solar—offer a unique opportunity to produce H_2 via electrolysis using surplus power. This H_2 can then be incorporated into the CTL process, where it would react with CO_2 to increase syncrude yields while simultaneously lowering net carbon emissions. This approach not only improves the carbon efficiency of CTL operations but also provides a pathway for valorising waste CO_2, thus enhancing both the ecological and economic sustainability of CTL facilities [5].

However, the economic feasibility of this integration remains a key question. H_2 production is the most significant operating cost in this process and a high-level economic assessment can offer insight into the upper bounds of acceptable H_2 costs, allowing for a rapid evaluation of whether the concept is economically viable. If such preliminary analysis is promising, it can guide more detailed feasibility studies.

This research presents a high-level economic analysis aimed at identifying the maximum H_2 cost that would allow its integration into CTL processes to be financially viable. The study evaluates break-even conditions and explores the influence of key variables such as electricity costs and CO_2 tax rates. By doing so, it provides an economic framework for guiding the integration of CO_2 conversion into CTL systems, with the dual objectives of enhancing fuel production and reducing CO_2 emissions—contributing meaningfully to the broader goals of carbon circularity and sustainable energy systems.

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2. Methodology

This study employs a comprehensive techno-economic analysis to evaluate the feasibility of integrating electrolytic hydrogen (H_2) into the Coal-to-Liquids (CTL) process for the purpose of CO_2 conversion. The approach consists of the following key components:

1. **Syncrude Composition and CO_2/H_2 Specifications**: Syncrude produced via a low-temperature Fischer–Tropsch process is typically highly paraffinic [6]. Accordingly, we assume an average carbon-to-hydrogen (C:H) ratio of 1:2, treating the –CH_2– unit as the representative molecular building block for stoichiometric calculations. This unit is used to determine the required flowrates of CO_2 and H_2 for the production of one barrel of syncrude.
2. **Economic Break-Even Analysis**: The maximum economically viable cost of H_2 is estimated based on the market value of syncrude, excluding additional operational expenditures. This analysis thus sets the maximum price of H_2 that would be profitable. If such preliminary analysis is promising, it can guide more detailed feasibility studies that considers OPEX and CAPEX costs. The analysis also considers the effect of carbon taxes on the economic competitiveness of H_2 integration.
3. **Energy Requirements**: H_2 production via electrolysis is assumed to require 55 kWh per kilogram of H_2 [7]. Power demand is assessed under scenarios with carbon conversion efficiencies of 40% and 60%, providing a range of energy input requirements for comparison.
4. **Sensitivity Analysis**: A sensitivity analysis is conducted to evaluate how variations in carbon efficiency influence CO_2 emissions, syncrude yield, and energy consumption. This helps to estimate the scale of power infrastructure needed under different implementation scenarios.
5. **Case Study: China:** A country-specific case study is conducted to explore the feasibility of implementing the process in China. The analysis incorporates local H_2 production costs and the availability of surplus renewable energy, providing a realistic regional context for the proposed integration.

This methodology provides insights into the economic and environmental potential of using electrolytic H_2 to convert CO_2 within CTL operations, offering a pathway toward more sustainable synthetic fuel production.

3. Calculations

1. **Syncrude Composition Assumption**: For simplicity, syncrude is assumed to consist entirely of –CH_2– units, with an average molecular weight of 14 kg/kmol based on the carbon content. This assumption reflects the highly paraffinic nature of syncrude typically produced via low-temperature Fischer–Tropsch synthesis.
2. **CO_2 and H_2 Requirements for Syncrude Production**
One barrel of syncrude is estimated to have a volume of 160 L and a density similar to that of octane, approximately 700 kg/m^3. This results in a mass of a barrel of syncrude:

$$Mass\ per\ barrel = \frac{160\ l * 700\frac{kg}{m^3}}{1000\frac{l}{m^3}} = 112\ kg$$

Using the assumed molecular weight of 14 kg/kmol for the –CH_2– unit, the number of kilomoles of –CH_2– in one barrel is: 112 kg / (14 kg/kmol) = 8 kmol per barrel.To produce one –CH_2– unit from CO_2 and H_2, the simplified stoichiometry can be written as: $CO_2 + 3\ H_2 \rightarrow -CH_2- + 2\ H_2O$ Therefore, for each kmol of –CH_2– produced, 1 kmol of

CO_2 and 3 kmol of H_2 are required. For 8 kmol of $–CH_2–$ (i.e., one barrel of syncrude), you therefore require 8 kmol of CO_2 and 24 kmol of H_2. The mass of H_2 required per barrel of syncrude is 24 kmol of H_2 x 2 kg/kmol = 48 kg H_2 per barrel of syncrude

iii. **Economic Break-Even Calculation for H_2:** Assuming the market price of syncrude is **$X** per barrel, the maximum break-even cost of H_2 (excluding all other operating and capital costs) is given by: Break-even H_2 price= $X per barrel / 48 kg of H_2 per barrel. This provides an upper-bound estimate for the economically viable price of H_2, offering a simplified benchmark for assessing feasibility.

4. **Impact of CO_2 Tax on Breakeven Price of H_2**

If a cost (or tax) is imposed on CO_2 emissions, it will directly affect the break-even calculation for H_2. This adjustment can be incorporated as follows:

Assume the CO_2 tax is **$Y** per tonne of CO_2. Since producing one barrel of syncrude consumes 8 kmol of CO_2, this corresponds to a consumption of CO2 of $8\ \text{kmol}\ CO_2/\text{barrel} \times 44\ \text{kg/kmol} = 352\ \text{kg}\ CO_2$ consumed per barrel of syncrude. If the tax rate of $Y per tonne is applied, the avoided emissions translate into a cost saving of:$Y*0.352 per barrel. This effectively increases the allowable break-even cost for H_2. The revised maximum H_2 price (excluding other costs) becomes: ($(X+0.352Y)/bbl)/48 (kg/bbl)where **X** is the market price of syncrude per barrel. The results of this calculation are presented in Figure 1.

The levelized cost of hydrogen (H_2) in 2030 is projected to range between $1.50 and $4.00 per kilogram, depending on geographical location [8]. According to Figure 1, for the integration of hydrogen into the CTL process to be economically viable, the market price of syncrude must exceed approximately $75 per barrel at a hydrogen cost of $1.50/kg, and around $190 per barrel at a levelized hydrogen cost of $4.00/kg.

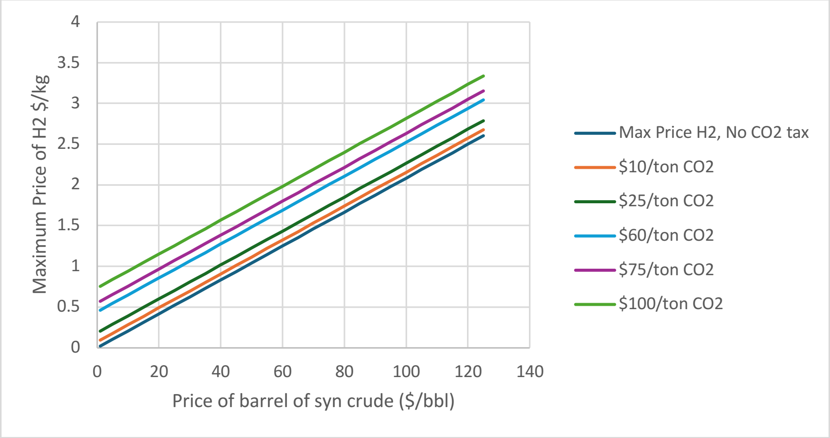

Figure 1: Maximum allowable hydrogen (H_2) price for break-even with syncrude production via CO_2 conversion to $–CH_2–$ using the Fischer–Tropsch process. The dark blue line represents the scenario where CO_2 is supplied at no cost. Additional lines represent varying CO_2 tax rates, showing how carbon pricing influences the minimum syncrude price required for H_2 integration to remain economically viable.

5. Case Study: Economic Viability in the Chinese Context

In China, H_2 production costs have been reported as low as \$2 per kilogram**.** At this H_2 price, the market price of syncrude must exceed \$100 per barrel for the integration of H_2 into the CTL process to be economically feasible, assuming no carbon tax.

However, when a CO_2 tax of \$10 per tonne is considered, the break-even price for syncrude decreases as shown in Figure 1. In this case, the process becomes economically viable at a syncrude price of approximately \$93 per barrel, still assuming H_2 costs \$2/kg. This highlights the important role of carbon pricing in enhancing the attractiveness of CO_2 conversion strategies.

Production and Energy Demands

Consider a facility that generates approximately 1.2 million tons of Syncrude annually.
This equates to 85.7 million kmol of CH_2 per year in the product.

Target Carbon Efficiency: 60%

Assuming a conservative carbon efficiency of 60% (based on overall mass and energy requirements), 57 million kmol of CO_2 are released year, equivalent to 2.5 million ton CO_2 per year. If all this CO_2 is converted to Syncrude, it corresponds to around an extra 0.8 million ton of Syncrude that might be produced each year which in turn corresponds to around 342,000 tons of H_2 needed annually. Assuming that the generation of 1 kg of H_2 necessitates 55 kWh of energy, we may illustrate the relationship between the necessary electricity and the additional barrels of Syncrude that can be generated, as shown in Figure 2.

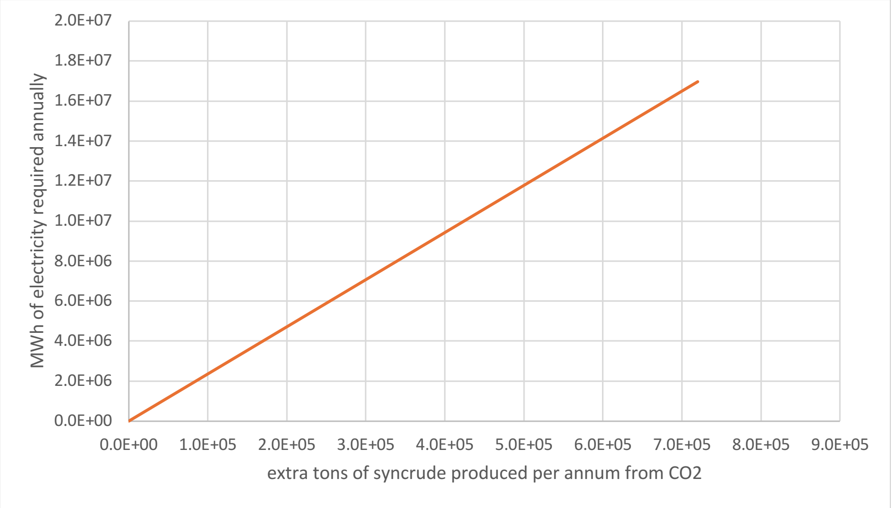

Figure 2: Annual Electricity Demands against Additional Tons of Syncrude Produced Annually from CO_2 - 60% Carbon Efficiency

To estimate the power requirements shown in Figure 2, it is assumed that electricity is available 24 hours per dayand that the plant operates for 350 days per year. These assumptions are intended to provide a rough approximation of the electricity infrastructure needed to support hydrogen production at scale. Figure 3 presents the corresponding minimum power capacity requirements as a function of additional syncrude output, offering insight into the scale of power generation infrastructure required for full integration.

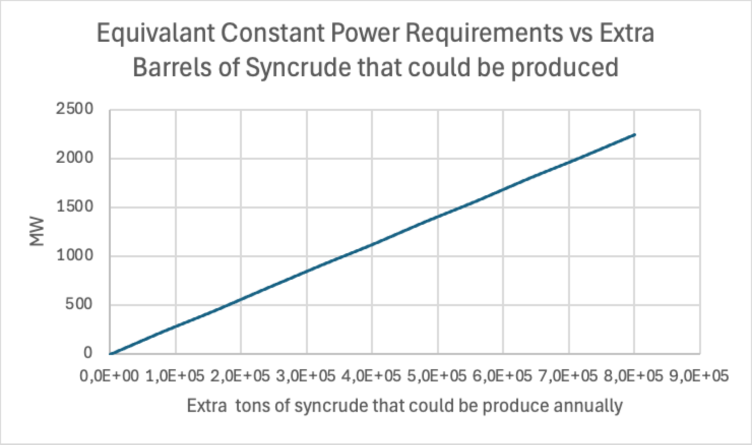

Figure 3: Constant power needs in relation to additional barrels of syncrude that may be produced.

Fully converting the CO_2 emissions into syncrude would require a continuous electrical supply of approximately 2.2 GW. According to Statista.com [9], Inner Mongolia has an installed wind power capacity of 36 GW. Therefore, utilizing less than one-tenth of this capacity could enable the production of an additional 0.8 million tonnes of syncrude annually, while simultaneously consuming approximately 2.5 million tonnes of CO_2 per year.

Target Carbon Efficiency: 40%

Current CTL plants typically operate at around 40% carbon efficiency. Repeating the calculations under this assumption yields a total of 129 million kmol of CO_2 emitted per year, equivalent to approximately 5.66 million tonnes annually. If all this CO_2 were captured and converted into additional syncrude, it could produce roughly 1.8 million tonnes of syncrude per year. This process would require approximately 771,000 tonnes of hydrogen annually.

Assuming the production of 1 kg of hydrogen requires 55 kWh of energy, the corresponding electricity demand is significant. Figure 4 illustrates the relationship between electricity consumption and the volume of additional syncrude that can be produced under this scenario.

To enable full conversion of CO_2 emissions at 40% carbon efficiency, a continuous electrical supply of approximately 5,000 MW (5 GW) would be required. This substantial energy demand underscores the critical importance of reliable and abundant renewable energy sources to enable large-scale CO_2 utilization in CTL operations. It also highlights the potential for such integration to support both economic and environmental sustainability goals.

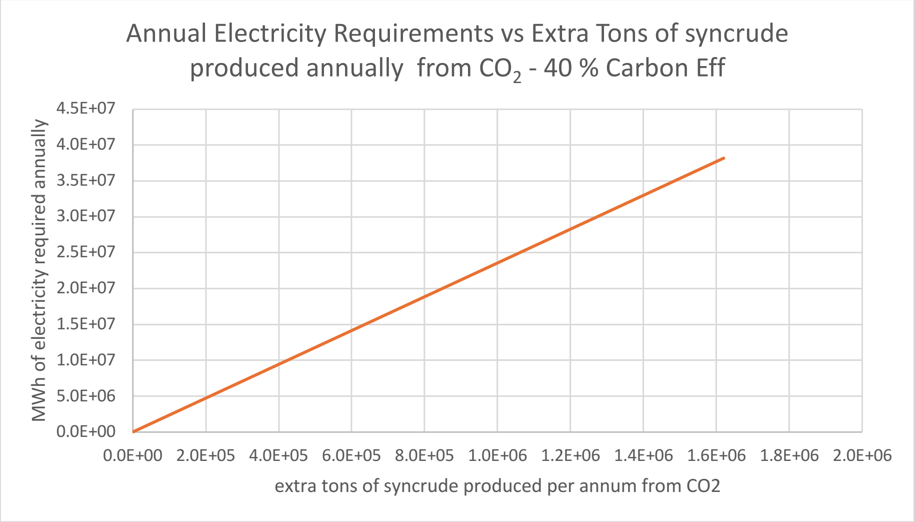

Figure 4: Annual Electricity Demands against Additional Tons of Syncrude Produced Annually from CO_2 - 40% Carbon Efficiency.

6. Conclusion

This study demonstrates the economic potential of incorporating hydrogen (H_2) into Coal-to-Liquids (CTL) processes to convert waste CO_2 into valuable syncrude. By evaluating multiple carbon efficiency scenarios and analyzing the break-even cost of hydrogen, the findings show that access to low-cost H_2 and surplus renewable electricity is critical to the viability of this approach.

In China, hydrogen production costs have been reported as low as $2 per kilogram. At this price, the market value of syncrude must exceed $100 per barrel for the integration of H_2 into the CTL process to be economically feasible, assuming no carbon tax. However, when a CO_2 tax of $10 per tonne is applied, the break-even syncrude price drops to $93 per barrel. This highlights the important role of carbon pricing in improving the economic attractiveness of CO_2 conversion strategies.

At a conservative carbon efficiency of 60%, converting 2.5 million tonnes of CO_2 annually could yield an additional 0.8 million tonnes of syncrude, requiring a continuous power supply of 2.2 GW. In contrast, at 40% carbon efficiency, approximately 5.0 GW of power would be needed to convert 5.66 million tonnes of CO_2 into 1.8 million tonnes of syncrude per year. These figures underscore the energy-intensive nature of CO_2 utilization and the necessity of a robust, reliable renewable energy infrastructure.

Regions rich in renewable energy resources, such as Inner Mongolia, are particularly well-suited to support large-scale CO_2-to-fuel conversion. Utilizing even a small portion of the region's existing wind power capacity could significantly reduce emissions while improving the sustainability and economic viability of CTL operations. Additionally, the implementation of carbon pricing mechanisms can further enhance the competitiveness of this strategy by lowering the syncrude price required for economic feasibility.

This analysis lays the foundation for future research and development aimed at optimizing hydrogen integration into CTL processes, supporting global decarbonization efforts and advancing the transition to a circular carbon economy.

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