

A COMPARATIVE TECHNO-ECONOMIC ANALYSIS OF RENEWABLE METHANOL SYNTHESIS FROM BIOMASS AND CO₂: OPPORTUNITIES AND BARRIERS TO COMMERCIALIZATION

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Abstract

Global demand for methanol as both a chemical precursor and a fuel additive is rising. At the same time, numerous renewable methanol production pathways are under development, which, if commercialized, could provide significant environmental benefits over traditional methanol synthesis pathways. However, it is difficult to compare technologies at different maturity levels, with differing feedstocks, and with significant differences in overall process design. Thus, there is a need to harmonize the analyses of renewable pathways using a consistent techno-economic approach to evaluate the potential for commercialization of various pathways. This analysis uses a novel cross-comparison method to assess near-term and long-term viability of both low- and high-maturity level technologies. The techno-economic assessment considers cost factors critical to market acceptance combined with carbon- and energy-efficiency assessments of three renewable pathways compared with a commercial baseline. We find that biomass gasification to methanol represents a near-term viable pathway with a high technology readiness level and commercially competitive market price. If cost-reducing technological improvements can be realized and scaled up in the CO₂ electrolysis pathways, the potential for higher carbon efficiencies may help drive market adoption of these more modular, direct conversion pathways in future markets as they present an opportunity to better support global decarbonization efforts through efficient waste carbon utilization.

Keywords: Methanol, techno-economic analysis, renewable carbon, waste carbon conversion, energy efficiency, carbon efficiency

Nomenclature

DOE	U.S. Department of Energy
MSP	minimum selling price
P2X	power-to-X
PEM	proton exchange membrane
R&D	research and development
TRL	technology readiness level

1. Introduction

The call to reduce global CO₂ emissions is at the forefront of research and development in the energy, transportation, and petrochemical industries. Policies and directives are in place encouraging governments and corporations to act on these global decarbonization endeavors. In the United States, California's Low Carbon Fuel Standard set a goal to reduce the carbon intensity of transportation fuels by at least 20% from a 2010 baseline by 2030 [1]. The European Union follows the Renewable Energy Directive (RED II), in which participating countries collectively contribute to emissions reduction targets, including reaching at least 32% renewable energy by 2030 [2]. Each respective policy installation supports the overarching goal of net-zero global emissions by 2050 [3, 4]. There is an opportunity to intersect multiple sectors via

the adoption and commercialization of renewable technologies for methanol production.

Methanol has long been considered a possible fuel additive with a research octane number blending value typically in the range of 129–134, greater than methyl tert-butyl ether (MTBE), toluene, and alkylate [5]. Currently, blends of up to 15 volume percent are used in China [6, 7]. As a clean-burning fuel with extremely low sulfur, low NO_x, and low particulate matter emissions, methanol is also a candidate for drop-in replacement fuel [8]. This is an attractive option for the various transportation sectors that are employing more stringent emission guidelines, and for sectors that are difficult to electrify, such as marine shipping [8, 9], aviation [10], and heavy freight [11]. Across the board, industry leaders are actively seeking low-carbon liquid fuels to help reduce their respective carbon footprints

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[4]. In addition to fuels, methanol is an important polymer precursor and is used as a feedstock for established methanol-to-olefins technologies, which are increasing in capacity and utilization, putting methanol in the spotlight and global methanol production on the rise [12]. From 2006 to 2016, annual global methanol demand doubled from 40 to 80 million tonnes [13]. Recent data project the demand to continue to grow at an average annual growth rate of 4.3% through 2026 [14]. Methanol's breadth of utilization and increasing market size make it a valuable platform chemical for renewable technology adoption.

Over the last 10 years, roughly 55%–65% of global methanol production used natural gas as a feedstock, roughly 30%–35% used coal, and the remainder was made up by coking gas and other feedstocks [14]. Assuming a lower heating value of 20.1 MJ/kg methanol [15], typical natural gas production pathways have reported greenhouse gas emissions ranging from 32.0 to 45.5 gCO₂e/MJ methanol [16, 17]. Since 2010, increasing demand for methanol and the abundance of large coal reserves in China have led to higher utilization of coal gasification plants for syngas to methanol production [12, 14]. As of 2014, approximately 650 coal gasifier units were operating or under construction, and the number of units planned for 2019 was 1,300, nearly doubling coal gasification capacity [18]. However, the implementation of coal gasification to methanol comes at the cost of higher greenhouse gas emissions, ranging from 81.8 to 143.8 gCO₂e/MJ methanol, which runs counter to current global decarbonization efforts [17, 19].

A recent report evaluating methanol as a renewable fuel alternative for marine applications determined that methanol from traditional natural gas exhibits significantly (nearly five times) greater global warming potential compared to methanol from biomass [9]. Another report by the Methanol Institute presented a “green” methanol scenario with well-to-wheel emissions as low as 2 gCO₂/km, compared to conventional methanol with 83 gCO₂/km [20]. Despite renewable methanol technologies displaying markedly lower carbon intensities relative to petrochemical alternatives, methanol production from renewable feedstocks is typically challenged by lower energy efficiency and higher cost compared to traditional methanol.

In response to environmental challenges with conventional processes, novel process designs for synthesizing renewable methanol with a lower carbon footprint are accumulating in the literature. In addition to bolt-on solutions such as carbon capture units, research is also underway for upstream process modifications including the design of pathways utilizing renewable

feedstocks with an inherent lower overall carbon footprint. Specific feedstocks of interest, and those discussed in detail in this work, include biomass-derived syngas and CO₂.

The availability and utilization of biomass has been extensively studied for use as a renewable feedstock for fuels and chemicals. A recent report from the U.S. Department of Energy (DOE) finds that more than one billion U.S. tons of domestic biomass may be available by 2040, despite competition from food, housing, and other existing end uses [21]. As such, biomass is an attractive renewable feedstock and several mature technologies for biomass conversion have been reported, many of which employ gasification to generate syngas [22–26]. Biomass-to-methanol processes already exist commercially, including Värmland's technology converting forest materials [27] and Enerkem's technology converting municipal solid waste, both via gasification [28].

CO₂ as a chemical feedstock is also gaining momentum, in part due to increasing interest in carbon capture and utilization. Catalytic CO₂ hydrogenation with renewable hydrogen (H₂) to methanol is one commonly referenced pathway in the literature [29–35]. Commercial development of this technology is currently being realized by Carbon Recycling International through their “Emissions-to-Liquids” processes [36]. Another major growth area for CO₂ utilization is in renewable power-to-X (P2X) technologies. P2X technologies offer a means to minimize the underutilization of renewable energy from solar and wind, which, as deployment continues to increase, are challenged by energy storage and intermittency issues. CO₂ P2X generally involves one of two pathways: either electricity is used to directly reduce CO₂ to products via an electrolysis step, or green H₂ is generated via H₂O electrolysis and then used in a downstream catalytic hydrogenation step [37–39].

Many P2X processes have reached the pilot scale and/or are already commercially viable [40–42], such as Blue Fuel Energy based in Canada, which uses a hybrid approach in which green hydrogen is used to convert CO₂ in tandem with traditional methanol synthesis (from natural gas) to produce a semi-renewable product [43]. Interest in P2X has also led to significant developments in electrosynthesis research, introducing novel process designs such as the direct electroconversion of CO₂-to-methanol, which is still currently at the bench scale [44, 45].

In this work, we evaluate the economic and commercial viability of renewable methanol synthesis pathways that have exhibited promise from a life-cycle perspective in the literature. To address how various process design and economic variations influence commercial adoption, we propose a holistic approach to compare methanol synthesis

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pathways on an economic, technical, and efficiency basis. In doing so, we identify four key process metrics to evaluate the feasibility of renewable methanol synthesis technologies versus the commercial baseline of natural-gas-to-methanol. The four metrics selected include minimum selling price (MSP), carbon efficiency, energy efficiency, and technology readiness level (TRL). These metrics help identify the economic feasibility of each pathway, the relative strengths and weaknesses of each technology, and whether commercialization for a given pathway is achievable in the near term or if additional research and development efforts are required. Of the numerous emerging renewable pathways to methanol, we evaluate three: (1) biomass gasification to methanol via a syngas intermediate, (2) electroreduction of CO₂-to-CO followed by catalytic hydrogenation to methanol, and (3) direct electroreduction of CO₂-to-methanol. While several other technologies in the literature exist, an additional output of this analysis is the ability to employ the results of this assessment to rapidly identify opportunities and barriers for commercialization which exist in similar technologies. Further, the analysis method outlined in this work can be applied across various fields of study.

The selected pathways are intended to span varying levels of technology maturity and efficiencies. This illuminates the strengths of current commercial processes, benchmarks relatively immature processes, and identifies the relative performance of each pathway as the technology improves. Additionally, these technologies were intentionally selected so that each subsequent pathway can be viewed as an adaptation of the previous. For example, the CO₂-to-methanol pathway utilizes the same downstream processing as the biomass-to-methanol pathway but has a different feedstock and upstream technology. Similarly, the direct CO₂-to-methanol uses the same feedstock and similar upstream conversion method as the indirect case, but with different operating parameters and downstream steps. This elucidates the changes derived from specific process modifications and allows for a thorough assessment from the front end to the back end of each technology. The resulting analysis derived from varied technologies highlights the benefits of developing a consistent baseline and generating a cross-comparison between metrics. This assessment ultimately evaluates the near-term economic viability of renewable methanol pathways and identifies the potential for improvements over time if technical performance metrics can be met through research.

2. Methods

2.1. Process Design

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The baseline design and underlying process assumptions for each pathway were selected to reflect a representative application of that technology. For the gasification and methanol synthesis steps, which are both mature and operated commercially, data from commercial literature for processes similar to Lurgi's methanol technology [46] were selected. For the lower-TRL emerging electrolysis-based pathways, which have not yet been commercialized, studies were ranked and selected based on reported current density values as a measure of process productivity. Using literature and published data for each pathway, three conceptual process models were developed in Aspen Plus V10 [47].

Material and energy flows were generated from the Aspen Plus models and applied in the techno-economic assessment. The process flow diagrams for each renewable methanol synthesis pathway are displayed in Figure 1. Figure 1A represents the biomass-to-methanol pathway, Figure 1B represents the indirect CO₂-to-methanol pathway, and Figure 1C is the direct CO₂-to-methanol pathway. More detailed information regarding the design and assumptions of each pathway is provided in sections 2.1.1–2.1.3.

2.1.1. Methanol synthesis via biomass feedstocks

Capitalizing on established technologies for both gasification and methanol synthesis, biomass gasification to methanol has been widely studied and, in a few cases, operated at the commercial level. The biomass gasification technology described in this assessment was modeled in detail and compiled in design reports generated by the National Renewable Energy Laboratory as a part of efforts funded by DOE's Bioenergy Technologies Office [48-50]. In the aforementioned design reports, detailed capital and operating expense breakdowns and specific performance metrics for the biomass gasification case can be located. In this process design, lignocellulosic biomass is pretreated and fed to an indirect gasifier along with steam. The biomass deconstructs to syngas (CO, CO₂, H₂), tars, and chars. Tars and chars are combusted as the primary source of heat for the gasifier, operated at 1,140.2 K and 243 kPa. Syngas is routed to a gas cleanup quench step and then sent to an acid-gas removal unit, where CO₂ concentration in the syngas is reduced to about 5% (by volume) and the excess is vented. Methanol synthesis is then operated isothermally at 523.2 K and 5,036 kPa over a commercial copper/zinc oxide/alumina catalyst [51]. Methanol is condensed and separated from the unreacted gases, which are recycled to the synthesis reactor (Figure 1A).

A summary of key process metrics for the biomass-to-methanol process is shown in Table 1.

Table 1. Key parameters for biomass-to-methanol

Metric	Assumed Value	Ref.
Feedstock		
Type	Biomass: 50% clean pine, 50% forest residues	[49]
Cost	\$66.78/dry tonne	[49]
Feed rate	2,000 dry tonnes/day	[48]
Gasification		
Temperature	1,140.2 K	[48]
Pressure	243 kPa	[48]
Tar Reforming		
Temperature	1,147.2 K	[48]
Pressure	198 kPa	[48]
Methanol Synthesis		
Temperature	523.2 K	[48]
Pressure	5,036 kPa	[48]
Methanol Degassing and Recovery		
Crude methanol purity (mol %)	97.0%	[48]
Methanol product purity (mol %)	99.4%	[48]

In addition to the baseline commercial design, two scenarios were considered to investigate the potential for increasing the carbon and energy efficiency of the process. In the first “renewable energy scenario,” renewable electricity is utilized as a supplemental energy source in place of a portion of syngas normally diverted for process fuel use, as shown in Figure 1A. In the baseline case, enough syngas is diverted to the combined heat and power generation system to meet the total heat and power requirements of the plant. In the alternative renewable energy scenario, only enough syngas is diverted to meet the heat requirements, and the remaining power demand is met by importing renewable electricity. In the second “CO₂ utilization scenario,” CO₂ scrubbed from the acid-gas removal is combined with imported renewable H₂ and fed to a reverse water-gas shift reactor yielding additional CO for the methanol synthesis step, which would otherwise be lost as CO₂ emissions (in Figure 1A as “Acid-gas removal CO₂”). The reverse water-gas shift reaction is shown in Equation 1:



2.1.2. Indirect CO₂-to-methanol via syngas intermediate

The indirect CO₂-to-methanol pathway uses a hybrid approach of upstream low-temperature CO₂ electrolysis combined with conventional methanol synthesis (Figure 1B). In the indirect baseline [52], CO₂ is reduced over a carbon nanotube doped silver (Ag) electrocatalyst reaching

a current density, faradaic efficiency, and whole-cell voltage of 350 mA/cm², 98%, and 3 V, respectively. However, acknowledging that CO₂ electrolysis is a nascent technology and will continue to improve over time, we also consider an alternative future scenario to account for technological improvements over time that assumes a whole-cell voltage of 2 V at a faradaic efficiency of 95% and current density 1,500 mA/cm². In both cases, renewable H₂ produced from proton exchange membrane (PEM) H₂O electrolysis [53] is imported and mixed with the produced CO to create a syngas mixture that then undergoes traditional methanol synthesis and purification as described in Section 2.1.1. Similarly, the same capital and operating assumptions are utilized for the downstream conversion steps as were in the biomass gasification case.

2.1.3. Direct CO₂-to-methanol electrolysis

In the direct CO₂-to-methanol electrolysis pathway, CO₂ is reduced to methanol in a single step using a low-temperature electrolyzer. Unlike the biomass- and H₂-mediated pathways, which currently operate at the commercial or pilot scale, direct CO₂ electrolysis pathways are comparatively immature and currently exist solely at the bench scale. Starting from a low-TRL point, it should be noted that significant uncertainty exists around the process design, scale-up, and stability of these processes.

Currently, the highest productivity direct CO₂-to-methanol study has reported methanol faradaic efficiencies of over 77% at cell voltages of 2.7 V, reaching total current densities of 41.5 mA/cm² using a copper selenide electrocatalyst in a laboratory “H-cell” reactor [44]. Reported byproducts during direct CO₂-to-methanol electrolysis include H₂, CO, and HCOOH, which are subsequently purified via pressure swing adsorption and distillation stages and recovered for sale as coproducts. Similar to the electrosynthesis of CO noted in Section 2.1.2, we also consider a future scenario that accounts for technological improvements in which we assume faradaic efficiencies of 95%, cell voltage of 1.8 V, and current density of 1,500 mA/cm² based on the performance of similar scaled-up electrolysis systems (e.g., PEM H₂O electrolyzers) [53].

2.2. Operating Costs

Renewable electricity is used in the biomass-to-methanol sensitivity case and both CO₂-to-methanol pathways to facilitate methanol synthesis. This assessment assumes a price of \$0.068/kWh, consistent with the 2019 average price of solar energy [54]. Recognizing that the price of electricity varies regionally and will likely continue to fall in the future, we assume a future case of \$0.02/kWh.

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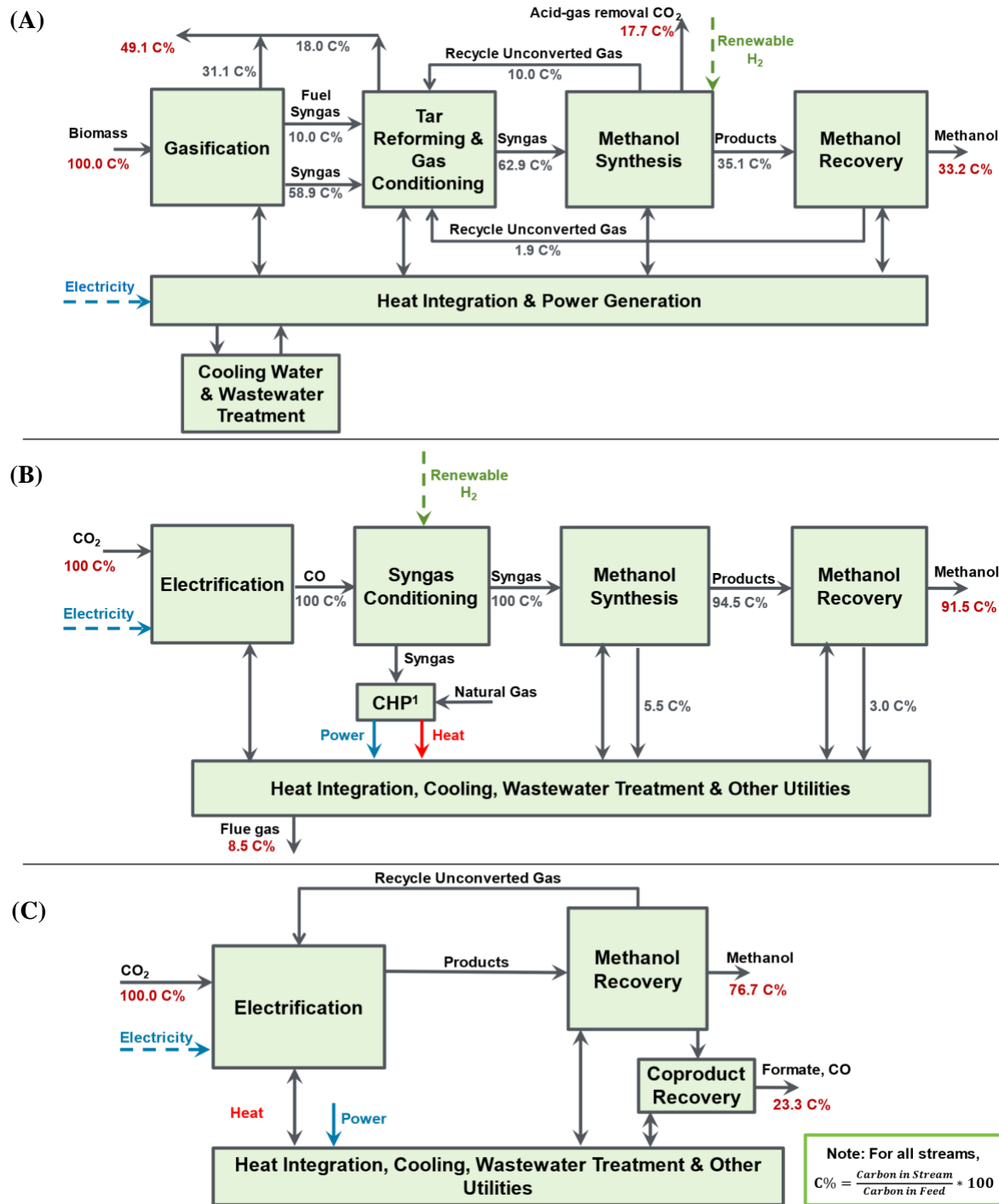


Fig. 1. Process flow diagrams for the three renewable methanol synthesis pathways: (A) biomass-to-methanol, (B) combined CO₂ electrolysis and H₂O oxidation for syngas conversion to methanol (indirect electrolysis), and (C) direct CO₂ electrolysis to methanol. Percentages show baseline carbon flows for internal (grey) streams and external (red) streams normalized by amount of carbon in the feedstock. CHP = combined heat and power. Process flow diagrams for the renewable sub-cases are located in the SI (Fig. S- 1-Fig. S- 4).

Renewable hydrogen is consumed in the CO₂ utilization scenario for biomass-to-methanol and in the indirect CO₂-to-methanol cases. We assume a base cost of \$4.50/kg H₂ and a future minimum cost scenario of \$1.38/kg derived

from DOE's Hydrogen Analysis (H2A) PEM electrolysis model [53].

The cost of captured CO₂ varies broadly depending on several factors, including concentration of CO₂, quantity and type of impurities, and type of capture technology. Flue

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gas streams with higher concentrations of CO₂ include those from fertilizer plants, ethanol fermentation facilities, and natural gas wells, and thus typically have lower capture costs [45]. Capture costs from these facilities range from approximately \$20–\$25/tonne CO₂ [55]. Facilities with lower concentrations of CO₂ in the flue gas stream such as coal and natural gas-fired power plants have capture costs ranging from \$40–\$125/kg [55]. We assume a pure stream of CO₂ is required for this assessment; however, we do not assume a specific CO₂ source. Herein we have assumed a baseline cost for CO₂ of \$40/tonne and a future cost of \$25/tonne. To address uncertainty in cost and purity of the CO₂ stream, we assess a range of CO₂ feedstock costs in a subsequent sensitivity analysis. Table 2 summarizes the current (baseline) and future operating costs for electricity, H₂, and CO₂.

Table 2. Summary of operating costs for the current baseline scenarios and future scenarios.

Operating Costs	Current	Future	Unit
Renewable electricity	0.068	0.020	\$/kWh
Renewable H ₂	4.50	1.38	\$/kg
CO ₂ feedstock	40	25	\$/tonne

2.3. Techno-Economic Analysis

Material and energy balances were generated via the Aspen Plus models described in Section 2.1. Previous chemical plant designs [48, 49] and vendor quotes were used to calculate capital and operating expenses and then used in a discounted cash flow rate of return analysis [50, 56, 57]. The economic viability of the process is based on the calculated methanol MSP, which represents the minimum price that methanol must sell for in 2016 U.S. dollars to generate a net present value of zero for a 10% internal rate of return, assuming a 30-year plant life and 21% income tax rate. In other words, the MSP is the plant gate price at which total revenue is equal to the sum of operating costs, return on investment, and income tax. To compliment the MSP, payback period was also calculated to understand investment risk. A thorough discussion of the payback period is provided in the SI.

The capacity of methanol production was based on the lignocellulosic biomass production at a fixed feedstock rate of 2,000 dry tonnes/day [48]; therefore, each model was scaled to have annual methanol production of about 291 million kilograms for consistency. A summary of financial parameters is given in Table 3.

Table 3. Summary of financial parameters

Description of Assumption	Assumed Value
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Internal rate of return	10%
Plant financing by equity/debt	40%/60% of total capital investment
Plant life	30 years
Income tax rate	21%
Interest rate for debt financing	8% annually
Term for debt financing	10 years
Working capital cost	5% of fixed capital cost (excluding land purchase cost)
Depreciation schedule	
General plant	7-year MACRS ^a schedule
Steam plant (if applicable)	20-year MACRS schedule
Construction period (spending schedule)	3 years (8% Y1, 60% Y2, 32% Y3)
Plant salvage value	No value
Startup time	0.5 years
Revenue and costs during startup	Revenue = 50% of normal Variable costs = 75% of normal Fixed costs = 100% of normal
On-stream percentage after startup	90% (7,884 operating hours per year)

^a Modified accelerated cost recovery system

3. Results

3.1. Minimum Selling Price

For each pathway, an MSP was derived using the approach detailed in Section 2.4. The underlying economic assumptions for each of the modeled renewable pathways were held constant to ensure a uniform baseline that is not obscured by varying financial parameters. Annual methanol pricing data from Methanex Corporation from 2010 to 2020 display a range of methanol prices from \$0.25–\$0.63/kg [58, 59]. More recently, between 2018–2020, methanol prices averaged \$0.30/kg (China) and \$0.41/kg in U.S. dollars [58, 59]. The average commercial baseline cost for methanol utilized for this assessment was determined specifically for the natural-gas-to-methanol process at \$0.33/kg [60]. According to data from IHS, feedstock and operating expenses contribute most of the commercial cost (about 78%) [60] (commercial baseline as shown in Figure 2).

A comparison of the methanol MSP for each pathway and the breakdown of total MSP including individual contributions from feedstock, hydrogen, electricity, and capital expenses is shown in Figure 2. As shown, the biomass-to-methanol pathway achieves a baseline cost of \$0.39/kg. This falls within the reported range of historical global methanol prices and suggests that there may be

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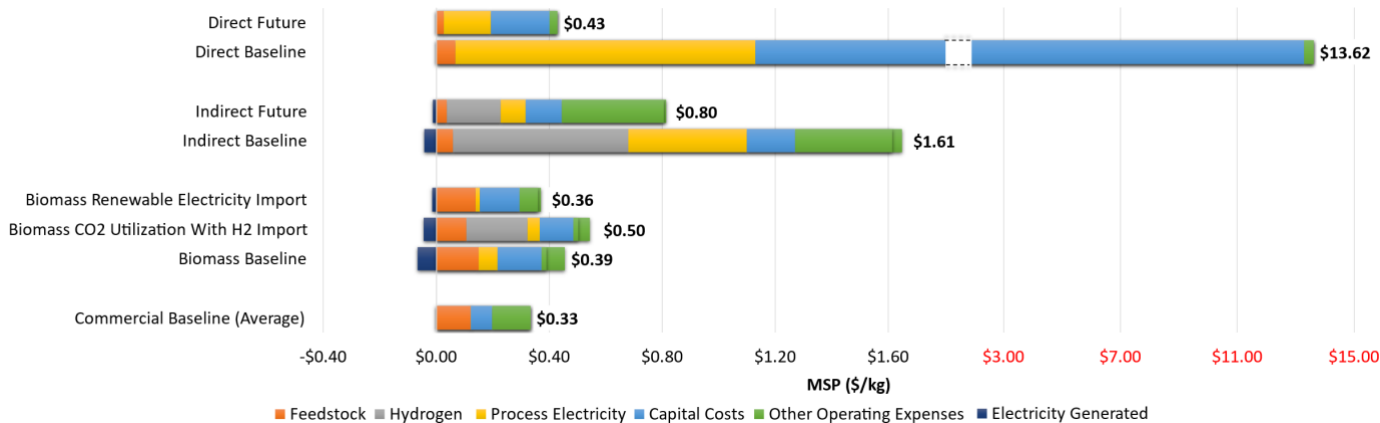


Fig. 2. Minimum selling price comparison for sustainable pathways versus commercial baseline. Cost breakdown includes feedstock (biomass or CO₂), hydrogen, imported electricity for process operation or excess electricity, capital costs and other operating expenses. *Note: the x-axis scale changes after \$1.60/kg to accommodate the direct baseline scenario.

opportunities in some markets for biomass-derived methanol. With the assumed baseline cost of hydrogen at \$4.50/kg, the CO₂ utilization sensitivity case increased the MSP by 29% to \$0.50/kg. However, greater carbon utilization may have the potential for MSP reduction at more reduced hydrogen costs. The electricity import sensitivity case provides a favorable impact on MSP, attaining a cost of \$0.36/kg with a baseline cost of electricity of \$0.068/kWh. Because this cost reduction can be achieved with current electricity prices, this is a promising near-term solution for reducing the biomass-to-methanol MSP and approaching cost parity with conventional methanol. In this scenario, cost savings are achieved through reductions in capital expenses associated with on-site power generation.

The baseline case for the indirect CO₂-to-methanol pathway exhibits an MSP of \$1.61/kg, approximately 490% greater than that of the commercial case. The largest cost drivers for this scenario are hydrogen and electricity under the assumptions of \$4.50/kg H₂ and \$0.068/kWh, respectively. Other operating expenses associated with the electrolyzer, including electrolyzer stack replacement costs and unconverted CO₂ recycle costs, also contribute significantly to the overall MSP in both the baseline and future cases. Reducing cell voltage and raising current densities should be a focus of ongoing R&D in effort to reduce the electricity requirement and decrease capital expenses of electrolysis. Such is the case investigated in the future indirect scenario shown in Figure 2, in which decreasing cell voltage from 3 V to 2 V reduces capital costs by greater than 20%. The future indirect scenario also assumes lower future CO₂, electricity, and hydrogen costs, helping to reduce the MSP by 50%.

In the direct CO₂-to-methanol case, the calculated MSP was significantly higher than the other two alternatives, at

\$13.62/kg. The high observed MSP can largely be traced back to the high capital intensity of the electrolyzer unit due to the low reported current densities. Specifically, at a total current density of only 41.5 mA/cm², the high total power demand to electrochemically reduce the fixed volume of CO₂ to methanol requires an enormous electrolyzer surface area on the order of 500,000 square meters. At an assumed cost of \$18,000/m² consistent with state-of-the-art PEM systems [53], this leads to a high capital intensity. In particular, our calculations show 89% of the cost contributions coming from capital expenses associated with the electrolyzer. Additionally, significant costs are incurred from the large electricity requirement. In the direct baseline case, electricity cost contributions alone (\$1.06/kg) are greater than the total MSP of the biomass and commercial pathways. By increasing current density and other technological metrics in the future case, the yield of methanol per unit area of the electrolyzer is increased, significantly reducing required size and capital expenses of the process and reducing the electricity required, resulting in an MSP of \$0.43/kg. Like the indirect case, future cost savings are also achieved through reductions in future market parameters such as electricity and CO₂ costs.

From the results discussed in Figure 2, key contributors to the MSP were identified. To illustrate the impact of individual technical and economic metrics on MSP and to address uncertainty within those metrics, Figure 3 shows the results of a sensitivity analysis around key process parameters. The midline of each chart represents the calculated MSP for the baseline scenario of the respective pathway, and the bars indicate the percent change to the MSP resulting from a change in the input of a sensitivity parameter. The inputs to each sensitivity scenario are listed on the vertical axis with the notation “Lower bound : Baseline : Upper Bound,” where the lower bound is the

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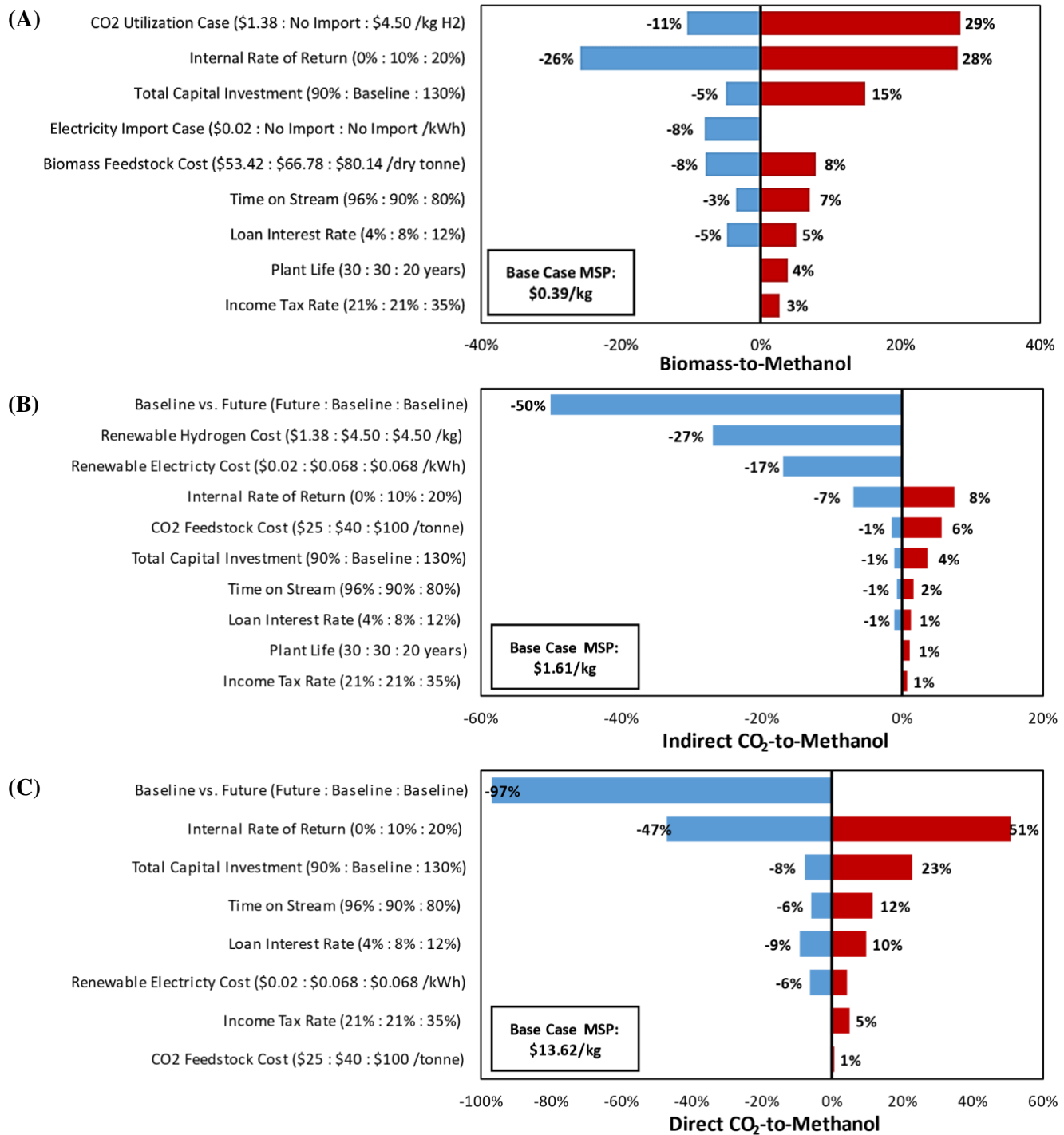


Fig. 3. Tornado plots displaying percent change to the baseline MSP for the three renewable pathways: (A) biomass-to-methanol, (B) combined CO₂ electrolysis and H₂O oxidation for syngas conversion to methanol (indirect electrolysis), and (C) direct CO₂ electrolysis to methanol.

value that yields a reduction in MSP and upper bound yields an increase in MSP. Upper and lower limits for H₂, CO₂, and electricity were selected as determined in Section 2.2. Financial and operational parameters such as internal rate of return, total capital investment, time on stream, and loan interest rate have upper and lower bounds consistent with

standard values in other Bioenergy Technologies Office publications [48, 57]. These parameters help address market fluctuations and process disruptions that may affect the overall MSP. Finally, a factor of $\pm 20\%$ was applied to the biomass feedstock cost to understand the impact of feedstock price variations in the biomass-to-methanol

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pathway. Each plot is sorted to show the parameter with the largest impact on MSP at the top of the plot and descends to the parameter with the least significant impact on MSP at the bottom.

The biomass-to-methanol pathway (Figure 3A) is most sensitive to H₂ cost in the CO₂ utilization scenario. If this change is implemented in the near term, current H₂ prices of \$4.50/kg yield less-desirable economic results with a 29% increase in MSP from the baseline (without CO₂ utilization). However, future H₂ cost projections of \$1.38/kg result in a methanol MSP reduction of 11% from the baseline. This indicates strong potential for future synergistic benefits for both cost and waste carbon mitigation to be realized within the biomass-to-methanol CO₂ utilization scenario. The renewable electricity scenario shows cost reduction potential in the near term as shown in Figure 2. However, future renewable electricity prices (\$0.02/kWh) result in a similar MSP as current prices (\$0.068/kWh), both showing MSP reductions of about 8%. Thus, implementing the renewable electricity scenario in the near term helps to reach more competitive prices; however, further drops in renewable electricity prices will not result in significant MSP improvements over time.

Beyond the potential economic improvements suggested by the future indirect CO₂-to-methanol pathway, which are partially contingent on successful research and development (R&D) efforts, the indirect pathway is most strongly affected by renewable hydrogen and renewable electricity costs. Similar to the biomass case, future H₂ price projections can significantly cut operating expenses for the indirect case by up to 27%. However, the time frame over which the indirect methanol synthesis pathway realizes cost benefits from H₂ cost reductions depends on H₂ developments. Additionally, substantial cost improvements are feasible from reductions in renewable electricity cost, with the future electricity price yielding a 17% reduction in MSP. The overall economic feasibility of the indirect pathway is ultimately dependent on each factor—CO₂-to-CO conversion, H₂ production, and renewable electricity prices—to decrease and improve over time.

In the direct CO₂-to-methanol pathway (Figure 3C), the MSP is dominated by capital expenses. As such, implementing the changes described for the future scenario are necessary for the direct pathway to reach market competitiveness. However, this will require significant R&D efforts to increase observed current densities to commercially viable levels and reduce capital and operating expenses to reasonable values. High sensitivity to internal rate of return, total capital investment, and time on stream is also observed for the direct CO₂-to-methanol case, emphasizing the importance of decreasing the total capital

of this process. In the current baseline scenario, reductions in renewable electricity costs from \$0.068/kWh to \$0.02/kWh results in a 6% reduction in MSP from the direct baseline, or \$12.74/kg methanol. Because the direct pathway is currently so heavily controlled by capital expenses, the effect of smaller contributors is less obvious. However, if research progresses to reduce the overall capital intensity of this pathway, reductions in other key cost areas will be essential for market competitiveness.

3.2. Carbon Efficiency

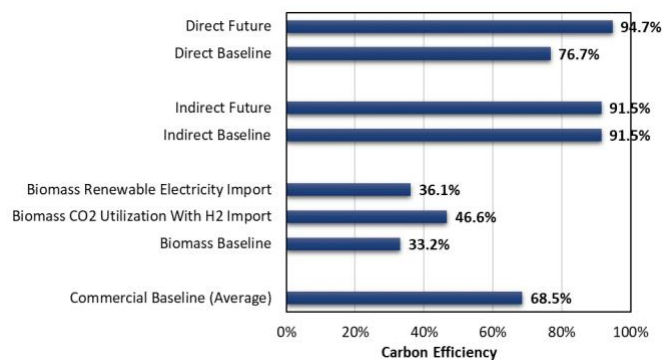


Fig. 4. Carbon efficiency for each renewable methanol synthesis pathway. Carbon efficiency is defined as the percentage of carbon from the feedstock that exits the process as methanol.

Carbon efficiency highlights the technical limitations unique to each pathway as it applies to carbon loss due to selectivity, feedstock challenges, and maximum theoretical production yields. Carbon flows normalized by carbon in the feedstock for each baseline scenario are displayed in Figure 1 and the overall carbon efficiency for every scenario is shown in Figure 4. As a basis for comparison, current commercial pathways exhibit carbon efficiencies ranging from 68%–75% [60].

Out of the four cases, the biomass-to-methanol pathway displays the lowest carbon efficiency, even under the more optimized scenarios including imported electricity or hydrogen. A significant limitation in the biomass-to-methanol pathway is carbon lost to tars and chars in the gasification step (about 31%). Tars and chars are solid carbon deposits on the circulating bed material and liquid aromatics that condense out of the gaseous product. Char formation is highly dependent on operating temperature of the gasifier. In the conceptual process design presented here, the gasifier operates at 1,140.2 K and process heat is assumed to come entirely from char combustion and recirculation of the hot fluidized bed material. Higher operating temperatures form less char, and thus theoretically increase carbon efficiency of biomass to gaseous product but require an external fuel source to

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provide heat, decreasing the energy efficiency of the process [48].

The carbon efficiency of the biomass-to-methanol pathway baseline case was 33.2%, significantly lower than the commercial baseline. Across the two sensitivity cases, importing H₂ into the synthesis loop to reincorporate carbon lost to CO₂ in the form of CO provided an improvement in carbon efficiency from 33.2% to 46.6%, whereas importing electricity and reducing the amount of carbon sent to fuel from 10% (Figure 1A) to 5.5% resulted in marginal gains in carbon efficiency (from 33.2% to 36.1%).

The indirect case (Figure 1B) achieves a carbon efficiency of 91.5% in both the baseline and future scenarios. Carbon losses in this pathway are primarily due to a small slipstream in the synthesis recycle loop and light hydrocarbons separated out in the methanol recovery step. These process off gases are routed to the combined heat and power system and burned as process fuel. Overall, the indirect CO₂-to-methanol scenario benefits from high carbon selectivity in the conversion of CO₂ to CO and efficient conversion of syngas to methanol through the use of recycles. Similar high carbon efficiencies are calculated for the direct CO₂-to-methanol pathway. As seen in Figure 4, the direct baseline scenario has a carbon efficiency of 76.7%. Carbon loss is due to the formation of byproducts such as formic acid and carbon monoxide. However, the direct CO₂-to-methanol case has the potential to reach carbon efficiency of approximately 95% in the future scenario if (1) unconverted CO₂ can be recycled back with high efficiency and (2) minimal carbon is lost to byproducts.

3.3. Energy Efficiency

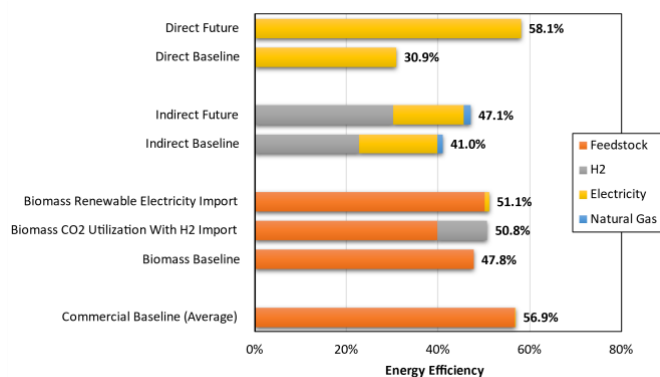
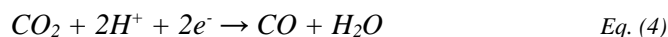
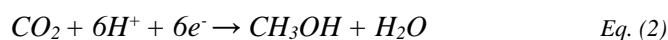


Fig. 5. Energy efficiency for each renewable methanol synthesis scenario. Relative contributions of the energy inputs into each pathway are represented in the breakdown of each bar.

Energy efficiency was calculated as the ratio of total energy in the methanol product on a lower heating value basis, divided by the total energy into the system. The major

energy inputs are summarized by four main components: energy in the feedstock, hydrogen, electricity, and natural gas (used for heating and separations purposes in the renewable pathways). Calculated energy efficiencies are reported for the four studied methanol synthesis pathways, showing a range of 28.2%–58.1% (Figure 5) depending on the specific case and assumptions. In comparing the three renewable pathways to the commercial baseline average of 56.9%, we show that the energy efficiencies are all lower under both current baseline and future case assumptions with the exception of the future direct case at 58.1%.

For the direct and indirect electrolysis CO₂-to-methanol cases, the most significant contributors to energy efficiency are the electrolysis operating assumptions. Although both processes require the transfer of six electrons to reduce CO₂ to methanol—shown in Eq. (2) for the direct pathway and Eq. (3)–(5) for the indirect pathway—differences in assumed cell voltage significantly impact the total overall energy demand.



The assumed cell voltage for direct methanol synthesis is 2.7 V based on recent experimental data, whereas the cell voltages for the H₂O oxidation and CO₂-to-CO electrolysis are at 2.0 and 3.0 V, respectively. When multiplying cell voltage by the electron demand per product (i.e., current) to get total power demand, the weighted average power demand of the baseline indirect case is less than that of the direct case due to the lower cell voltage of the H₂O oxidation step. Further, the reduced carbon selectivity of the direct baseline case also contributes to lower overall efficiency compared to the indirect baseline case. However, in the future scenario, reductions in cell voltage and improved faradaic efficiency drive the future direct case to an overall energy efficiency of 58.1%, higher than the future indirect case (47.1%). Additional heat and pressure are required in the indirect case for the thermochemical conversion process to convert the syngas to methanol, whereas the direct case operates at near-ambient conditions. These additional processing steps in the indirect case add additional energy burdens to the process, and limit overall energy efficiency improvements stemming from advancements in the electrolysis technology.

With the baseline biomass case relying predominantly on the energy inherent within the biomass as the main

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energy input, the lower energy efficiency compared to the commercial baseline can largely be traced back to the poor carbon efficiency as illustrated in Figure 1A. Specifically, some of the inherent energy in the incoming feedstock is lost to char, tars, and other light species and is not recovered with 100% efficiency for process use. Further, the biomass case employs several energy-intensive unit operations such as the tar reformer, acid gas removal, and methanol synthesis, which further drive-up energy usage. Process efficiencies are modestly improved through the use of renewable electricity but are only expected to reach ~51.1%.

The commercial baseline pathway primarily benefits from highly optimized conversion technologies, and efficient utilization of energy in the feedstock. In typical steam methane reforming, the reformer operates at about 1,023.2-1,073.2 K [61], comparable to the modeled biomass gasification temperature (1,140.2 K). However, biomass gasification is followed by another high temperature reforming step (1,147.2 K), whereas the commercial pathway may only require a water-gas shift reaction under mild reaction conditions (463.2-573.2 K) to reach optimal syngas compositions [61]. The inclusion of this second energy intensive step in the biomass gasification process design is a limitation when attempting to improve upon the energy efficiency of the pathway compared to the conventional baseline.

Unlike the biomass gasification pathway, the CO₂ electrolysis pathways do not utilize high-temperature unit operations. Rather, these processes rely on the efficient conversion of electrons to products. In the baseline scenarios for both the indirect and direct scenarios, cell voltages are relatively high, increasing the overall power demand per unit of product resulting in lower energy efficiencies relative to the commercial case. However, in the future scenarios, as cell voltage decreases, the overall power demand per unit of methanol decreases as well leading to, in the direct case, higher energy efficiency than the commercial case. Importantly, a secondary benefit in the CO₂ electrolysis cases is the carbon neutrality of the energy into the system. While the conventional process relies primarily on fossil natural gas, the direct and indirect pathways obtain most of their respective energy inputs from renewable electricity and renewable hydrogen.

3.4. Technology Readiness Level

An assessment of the TRL for each pathway was generated from DOE's Technology Readiness Assessment Guide [62]. The TRL is a qualitative assessment of the current state of research and development and is a useful indicator for estimating time to commercialization, with

lower TRLs requiring significant development efforts. Commercial installations of biomass gasification plants ranging from pilot to demonstration scale since as early as 1990 suggest a high TRL for the biomass gasification pathway, on the order of 7–9 [24].

The indirect pathway consists of essentially three technologies: CO₂ reduction to CO, H₂O electrolysis to H₂, and syngas conversion to methanol. Water electrolysis and syngas conversion to methanol are both commercialized and mature technologies with TRLs of 9 [42, 63]. However, CO₂-to-CO is approximately TRL 4, and is thus the limiting factor in time to commercialization.

Finally, the data used to derive the direct CO₂-to-methanol case are from small-scale, first principles experimentation. Therefore, the direct pathway is at about TRL 1-2 and will require significant R&D efforts and time to reach commercial-scale deployment.

4. Discussion

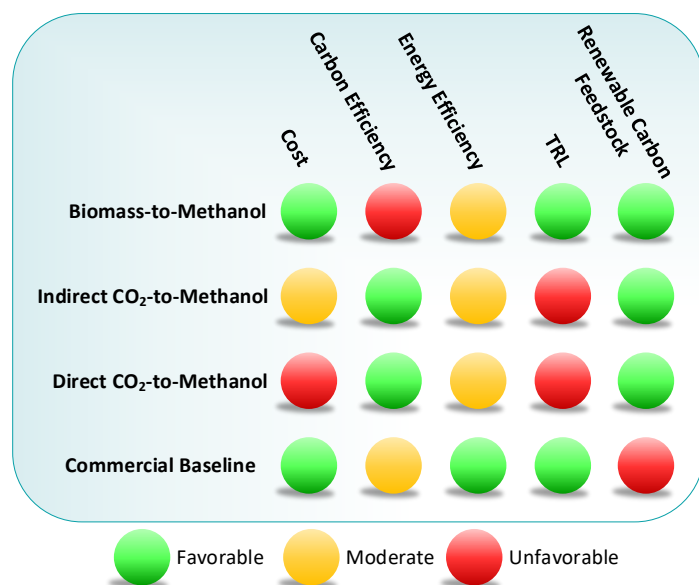


Fig. 6. Cross comparison of all four baseline cases on cost, carbon efficiency, energy efficiency and TRL, using matrix approach highlighting the favorability of each pathway. An additional metric has been added to highlight the use of renewable carbon.

The overarching goal of this analysis is to evaluate the economic and technological merits of various pathways to methanol and to investigate methods for increasing the competitiveness of renewable pathways. Analyzing MSP, carbon efficiency, energy efficiency, and TRL simultaneously helps to identify the factors that are most important for near-term or long-term deployment of renewable methanol technologies. In this analysis, we have produced three renewable methanol process designs with a set of consistent assumptions to generate a cross-

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comparison. A high-level representation of this analysis for each baseline scenario is shown in Figure 6.

In order to compete with conventional methanol synthesis routes in the near-term, a renewable pathway must be at a high enough TRL to be deployed at scale, and the MSP must be comparable with current methanol market prices. Based on our assessment of TRL, the biomass-to-methanol scenario is the only renewable methanol synthesis pathway which could potentially be deployed at scale in the near-term. From a cost perspective, the biomass gasification to methanol pathway of \$0.39/kg can currently contend with the economic performance of conventional methanol synthesis. The use of commercialized processes (i.e., syngas conversion to methanol) is a primary driver for reduced costs. Further, the biomass pathway's utilization of commercialized methanol synthesis processes creates the opportunity for integration with existing conventional methanol plants, decreasing transition time and cost. Biomass gasification technologies unsurprisingly perform well from cost and TRL due to existing infrastructure and currently operating plants.

However, this analysis also identifies the technological challenges presented by each technology preventing either large scale deployment or significant improvement over conventional methanol production. For example, the biomass scenario lacks in carbon efficiency and energy efficiency compared to the conventional methanol scenario. The renewable electricity and hydrogen scenarios can yield efficiency improvements in the near-term, though depending on the resource price, this may lead to a slight increase in methanol cost. Despite the slightly lower efficiencies, it is important to note that the biomass-to-methanol pathway utilizes a renewable carbon feedstock, and thus represents a viable near carbon-neutral pathway which can serve as a transition to more sustainable options in the long-term.

The CO₂ electrification technologies are in the nascent stages of development, thus techno-economic assessments for at-scale, mature embodiments of this technology are infrequent in literature. This assessment helps to shed light on the current state-of-the-art performance and identifies avenues for future improvement. As the baseline scenarios stand for the indirect CO₂-to-methanol and direct CO₂-to-methanol pathways, high cost and low TRL prevent their adoption in the near-term. Low TRL presents higher risk associated with process scalability and generates uncertainty surrounding the final commercial design, particularly for the direct CO₂-to-methanol conversion pathway.

However, as we look to the future and governments and businesses more strongly consider environmental costs in

addition to economic costs, the indirect and direct renewable synthesis pathways could be promising alternatives to conventional methanol synthesis. Looking at long-term deployment of the electrolysis cases, technology improvements across several platforms including renewable electricity generation, renewable H₂ production, and CO₂ electrolysis would allow these comparatively lower TRL technologies to reach commercial scales. Due to these projected improvements, the future costs for the indirect and direct electrolysis cases are expected to decrease considerably from their current baselines down to \$0.80/kg and \$0.43/kg, respectively. Though these are not quite as competitive the biomass case, policies and incentives for utilizing waste carbon may play a role in future renewable markets, making these pathways more attractive. As such, the transition from biomass (or fossil) derived methanol to CO₂-to-methanol technologies in the future can be justifiable on both TRL and economic bases and while offering significant gains on the environmental front.

Similar to the biomass pathway, the indirect CO₂ electrolysis pathway can be integrated with conventional methanol synthesis facilities. Thus, in the long-term scenario as CO₂-to-CO technology matures, transition time and costs can be reduced through co-location of electrolysis with conventional methanol synthesis plants. The direct CO₂-to-methanol pathway is currently at the lowest TRL, indicating the longest time to commercialization. However, since the direct CO₂-to-methanol displays the most promising environmental metrics, and reduced costs in the future scenario, it may be beneficial to integrate this pathway into the methanol market in the long-term.

5. Conclusion

Commercial methanol pathways operate at large scale and low cost and with moderate carbon and energy efficiencies. Therefore, a viable renewable methanol technology should meet or exceed the current commercial metrics to drive adoption at scale. This work presented a novel cross-comparison method to assess the economic and environmental potential of renewable methanol technologies. These results gave insight into the cost of nascent technologies including the electrochemical reduction of CO₂ to products and how they compare to commercial technologies. The results show the biomass gasification-to-methanol pathway is capable of meeting market-competitive costs and displays a high TRL, representing a pathway with great near-term potentials. Despite lower carbon utilization metrics compared to the conventional methanol synthesis baseline, the biomass case utilizes a renewable carbon source, which helps to reduce fossil resource consumption and approach carbon-neutral

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production of a critical platform chemical. However, efficiency metrics are key elements for impactful change in the ongoing global decarbonization efforts. Both indirect and direct CO₂-to-methanol pathways present energy efficiencies comparable to commercial pathways and exceptional carbon efficiencies, but at a cost. The direct CO₂ pathway is comparatively much lower in TRL and requires the most substantial R&D efforts pushing commercialization into the long term, whereas the indirect CO₂ pathway may be achievable in less R&D time if electrolysis costs can be dramatically reduced.

Near-term commercialization will largely be driven by TRL and market acceptance through cost parity. As global priorities begin to shift and greater consideration is given to sustainability metrics for commercial deployment of technologies, long-term solutions will require both improved carbon and energy efficiencies over the commercial baseline, which may be possible through the indirect and direct electrolysis pathways. These long-term solutions are essential for meeting global decarbonization targets. Consequently, future analyses should consider process designs that are optimized across a variety of economic and environmental metrics rather than solely economic drivers.

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