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Centre for Sectoral Economic Performance

Sustainable Methanol Production via Syngas-Mediated Pathways:

A Techno-Economic Comparison

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July 2026

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Why Methanol Matters

Methanol is a versatile platform molecule that can accelerate industrial decarbonisation across multiple sectors. Beyond its long-established role as a feedstock for the chemical industry, methanol can be used directly as a low-carbon fuel in maritime transport and is increasingly being adopted to meet emerging emissions regulations in shipping. It can also serve as an intermediate for the production of a wide range of sustainable fuels, including gasoline, diesel and sustainable aviation fuels (SAF) via methanol-to-jet pathways.

This flexibility makes methanol a strategic link between renewable energy, carbon utilisation and sustainable manufacturing. By converting captured CO_2 and low-carbon hydrogen into a transportable liquid product, methanol provides both a means of storing renewable energy and a pathway to defossilise hard-to-abate sectors while supporting the production of essential chemicals and fuels.

Executive Summary

This research provides a comprehensive techno-economic evaluation of low-cost, sustainable syngas generation and its downstream conversion into sustainable methanol. Investigating the transition from carbon-intensive fossil-based synthesis to low-carbon alternatives necessitated by 2050 net-zero targets, the study benchmarks four primary technological routes - conventional thermocatalytic reverse water-gas shift (rWGS), advanced chemical looping (CL-rWGS), plasma-assisted rWGS, and solid oxide electrolyser cell (SOEC) electrolysis - against the incumbent Steam Methane Reforming (SMR) baseline. By establishing a rigorous and comparable framework, the analysis seeks to identify the dominant economic drivers and the relative resilience of each technology within an emerging sustainable methanol economy. The strategic importance of methanol in this transition stems from its versatility as a high-density energy storage medium and a critical precursor for the chemical industry. Furthermore, sustainable methanol is increasingly recognised as a primary solution for decarbonising hard-to-abate sectors, serving as a drop-in shipping fuel to meet maritime emission mandates and a vital feedstock for the production of Sustainable Aviation Fuels (SAF) through alcohol-to-jet pathways.

Using Aspen Plus v14, a standard chemical process simulation software package, each pathway was standardised to a production capacity of c. 200 tonnes per hour of high-purity methanol and evaluated within the economic context of a new-build facility in the United Kingdom. Uncertainty analysis was utilised to quantify the impact of volatile feedstock and energy markets on the resulting Net Production Cost (NPC). This methodology ensured a robust assessment of economic risk across all evaluated pathways, accounting for the inherent price uncertainties associated with low-carbon hydrogen, captured carbon dioxide, and industrial electricity.

The findings reveal that chemical looping (CL-rWGS) represents the most economically competitive sustainable pathway, yielding a mean NPC under uncertainty of 2.09 USD per kilogram of methanol, followed by the plasma-assisted route at 2.43 USD per kilogram. In contrast, the conventional rWGS and SOEC-based electrolysis pathways demonstrate significantly lower competitiveness, with mean NPC values under uncertainty of 3.04 and 3.61 USD per kilogram, respectively. Across all evaluated technologies, the operational expenditures – specifically the procurement of low-carbon hydrogen, captured carbon dioxide, and electricity – are the dominant cost driver, whereas capital expenditures remain a comparatively minor component of the total production cost.

A targeted cascade analysis outlines a viable trajectory for the leading CL-rWGS configuration to achieve commercial competitiveness. While utilising strategic low-carbon feedstocks – specifically emerging white hydrogen and biogenic CO_2 – compresses the initial Net Production Cost (NPC) to 0.68 USD per kilogram, this remains slightly above the 0.60 USD per kilogram fossil benchmark. However, by sequentially integrating literature-backed supply-chain advancements, the central-case NPC can be compressed further to approximately 0.57 USD per kilogram, successfully achieving parity with conventional fossil fuels. This critical reduction is enabled by three primary strategic levers: electricity tariff reforms and renewable co-location, advanced geological optimisations for white hydrogen, and the deployment of integrated biogenic CO_2 transport networks.

Ultimately, achieving economic parity with the natural gas-derived benchmark of 0.60 USD per kilogram under generalised market distributions remains a formidable challenge that cannot be bridged by capital cost reduction alone. Instead, the results suggest a required shift in research focus towards aggressive process intensification and the development of next-generation catalysts to improve single-pass conversion rates and system-wide energy efficiency.

Furthermore, strategic site selection must prioritise regions offering access to ultra-low-cost renewable electricity and biogenic CO2 sources – such as those derived from biorefineries – to mitigate the substantial operational expenditures that currently serve as the primary hurdle to market competitiveness. Long-term market viability will depend upon robust policy mechanisms, including carbon pricing, long-term Contracts for Difference (CfD), and sector-specific fuel mandates. Finally, these transitions must be underpinned by a comprehensive Life Cycle Analysis (LCA) to ensure that economic optimisations remain authentically aligned with genuine climate neutrality objectives and prevent the unintended shifting of environmental burdens across the value chain.

1. Introduction

Synthesis gas, or syngas – a versatile mixture consisting primarily of hydrogen (H_2) and carbon monoxide (CO) – has served as the foundational intermediate for the modern chemical industry for over a century [1]. The production of these gas mixtures first gained industrial prominence in the late 19th century, when they were obtained by reacting steam with incandescent coke at temperatures near 1,000 C to produce water gas [1,2]. Initially utilised as a fuel, water gas soon became a vital source of chemical precursors for the large-scale production of ammonia following the startup of the first commercial Haber-Bosch process in 1913, and later for the industrial synthesis of methanol [1,3]. During the 1920s and 1930s, the industrial focus shifted toward natural gas through the development of catalytic Steam Methane Reforming (SMR), a process first applied commercially in 1930 that remains the dominant global pathway today [1,4]. While SMR and coal gasification are highly mature and cost-effective, accounting for nearly 47% of current global syngas production, they are inherently carbon-intensive [5,6]. These conventional processes contribute significantly to global anthropogenic greenhouse gas emissions, creating a critical requirement for sustainable alternatives that can meet ambitious 2050 net-zero targets [7].

As the global energy landscape transitions toward a circular carbon economy, Power-to-X (PtX) pathways have become a strategic route for producing low-carbon syngas for downstream chemicals and fuels. These sustainable alternatives utilise captured carbon dioxide (CO_2) as a primary carbon feedstock and renewable or low-carbon hydrogen as a high-density energy carrier [8]. The primary chemical mechanism driving this transformation is the reverse water-gas shift (rWGS) reaction, an endothermic process that thermodynamically favours the production of syngas at elevated temperatures, typically exceeding 700 °C [9,10].

Sustainable syngas can be synthesised through a diverse range of technological approaches, each presenting unique trade-offs. Thermocatalytic reverse water–gas shift (rWGS) is among the most mature, with core reactor technology at approximately TRL 6 and demonstrated at facilities such as the George Olah Plant [11] and the MefCO_2 Project [12]. This approach employs high-temperature reactors and heterogeneous catalysts – typically transition metals such as nickel (Ni) or iron (Fe), as well as noble metals like ruthenium (Ru) – to drive the conversion of CO_2 with H_2 into CO-rich syngas [13]. While industrially compatible, its reliance on large gas-recycle loops and high compression ratios to overcome gas-phase equilibrium limitations presents a significant energy penalty and feedstock waste [1,14].

Photothermal rWGS has achieved breakthrough solar-to-enthalpy efficiencies approaching 40% with 100% CO selectivity at approximately 300 °C using AgK/Fe304 catalysts [15]. However, these solar-driven methods remain at an earlier stage of development than conventional thermocatalytic rWGS, with commercial deployment further constrained by solar intermittency, reactor scale-up challenges and efficiency losses under non-ideal operating conditions [14,16]. Emerging electrified pathways, such as plasma-assisted conversion, offer rapid kinetics by creating highly reactive ions and radicals that enable the reaction to proceed at lower bulk temperatures while maintaining high local temperatures in the plasma zone [17]. While offering rapid startup and shutdown times suitable for intermittent energy sources, these systems face hurdles regarding electrode durability and extreme electricity consumption [18,19]. Electrochemical reduction via Solid Oxide Electrolyser Cells (SOEC) provides high-purity product streams with O_2 as the only byproduct, but the technology is currently hindered by severe cell degradation and high capital intensity [20].

A fundamental shift in methodology is provided by chemical looping (CL-RWGS), which decouples the reaction into distinct redox half-cycles mediated by a solid oxygen carrier, such as iron-based materials or non-stoichiometric perovskites [21,22]. In this cyclic operation, renewable hydrogen reduces the metal oxide carrier to generate steam, followed by the re-oxidation of the carrier by CO_2 to produce high-purity carbon monoxide [21,23]. This spatial or temporal separation circumvents the global thermodynamic equilibrium constraints of the gas-phase reaction, enabling overall CO_2 conversions that can approach 100% [24]. Other innovations in CL-RWGS, such as the direct electrification of a porous metallic iron bed via Joule heating (10 W to 2,200 W), allow the reaction to be activated at significantly lower bulk temperatures (400 °C–700 °C) and provide the ability to process untreated flue gas directly, as the iron carrier acts as a sacrificial scrubber for SOx and NOx [25]

Despite extensive research into individual syngas production methods, a critical gap remains: there is no unified techno-economic analysis (TEA) that evaluates these state-of-the-art routes using standardised process and economic assumptions. This lack of standardisation is complicated by the fact that syngas is rarely traded as a commodity; instead, it is typically produced and consumed on-site as an intermediate for downstream chemicals and fuels. This localised use makes direct comparison between syngas technologies difficult and can obscure differences in efficiency, scalability and cost-competitiveness.

To address this issue, the present study benchmarks syngas production through its downstream conversion to methanol, which serves as the functional unit for the analysis. Methanol is selected because it is a major industrial outlet for syngas and a relevant platform chemical for both conventional chemical production and emerging low-carbon fuel applications [26]. Conventional methanol is produced mainly from fossil-derived syngas obtained from natural gas or coal, whereas alternative routes such as biomass or municipal solid waste gasification also rely on syngas cleaning, conditioning and subsequent methanol synthesis. This makes methanol an appropriate basis for comparing the low-carbon syngas generation routes assessed in this work without treating syngas as a standalone traded product.

The technological scope of this work encompasses four primary syngas production routes, selected to represent a broad spectrum of technological maturity and potential for process intensification. Conventional thermocatalytic reverse water-gas shift (rWGS) is included as the industry benchmark due to its advanced development and well-established catalyst systems. Advanced chemical looping rWGS (CL-rWGS) is evaluated for its ability to bypass thermodynamic equilibrium limits through cyclic redox operation. Additionally, direct-current plasma-assisted rWGS is considered for its rapid reaction kinetics and compatibility with modular, electrified operation, despite ongoing challenges with energy efficiency. Finally, solid oxide electrolysis cell (SOEC)-based CO_2 electrolysis represents a high-temperature electrochemical pathway that allows for a direct comparison with thermochemical routes in terms of system complexity and integration potential.

Consequently, this study establishes a consistent framework by integrating rigorous process simulation with a comprehensive Techno-Economic Analysis (TEA) and sensitivity evaluation across all four production pathways. To account for the high volatility of emerging feedstock markets, a dual-method uncertainty analysis is applied, comprising a variance-based Global Sensitivity Analysis (GSA) following the Sobol method and a probabilistic One-at-a-Time (OAT) analysis. Ultimately, this research identifies the dominant economic drivers and evaluates the relative resilience and competitiveness of each technology against the incumbent Steam Methane Reforming (SMR) benchmark within an emerging sustainable methanol economy.

The subsequent sections of this report are organised as follows. Section 2 details the core methodology, encompassing process modelling, techno-economic evaluation, and sensitivity analysis. In Section 3, the findings for all four evaluated pathways – conventional rWGS, CL-rWGS, plasma-assisted rWGS, and SOEC – are examined and benchmarked against the traditional SMR route. Section 4 evaluates potential cost-reduction pathways for sustainable methanol production using a cascade analysis. Section 5 presents the conclusions of the study, summarising the primary results and identifying the dominant economic hurdles. Finally, Section 6 provides an outlook, addressing the technological innovations and policy mechanisms essential for the transition to a sustainable methanol economy.

2. Methodology

The technoeconomic evaluation is performed by integrating rigorous process simulation with a comprehensive economic and sensitivity framework. Each of the four pathways – thermocatalytic reverse water-gas shift (rWGS), chemical looping rWGS (CL-rWGS), thermal direct-current plasma rWGS, and solid oxide electrolysis cell (SOEC) CO_2 reduction – is modelled at a nominal production capacity of approximately 200 t/h of methanol, equivalent to approximately 4,730 t/day. While this scale significantly exceeds current low-carbon demonstration facilities, standardising the design to this capacity is essential to mirror conventional, single-train commercial plants (c. 5,000 t/day) [27,28].

All process models are developed in Aspen Plus v14 [29], a commercial chemical process simulation package, using the Soave-Redlich-Kwong equation of state with the Boston-Mathias modification (SRK-BM) as the global property method. This thermodynamic package ensures accurate prediction of phase behaviour and vapour-liquid equilibria for high-pressure mixtures containing polar components such as methanol and water and non-polar gases like hydrogen, carbon monoxide, and carbon dioxide [30,31].

This study adopts a modular approach where four distinct technological routes are evaluated as alternatives for the generation of syngas, which is subsequently converted to methanol in a common downstream synthesis loop.

2.1 Process modelling

2.1.1. Syngas production pathways
The following four alternative routes are evaluated for the production of syngas from low-carbon hydrogen and captured carbon dioxide, as shown in Figure 1:

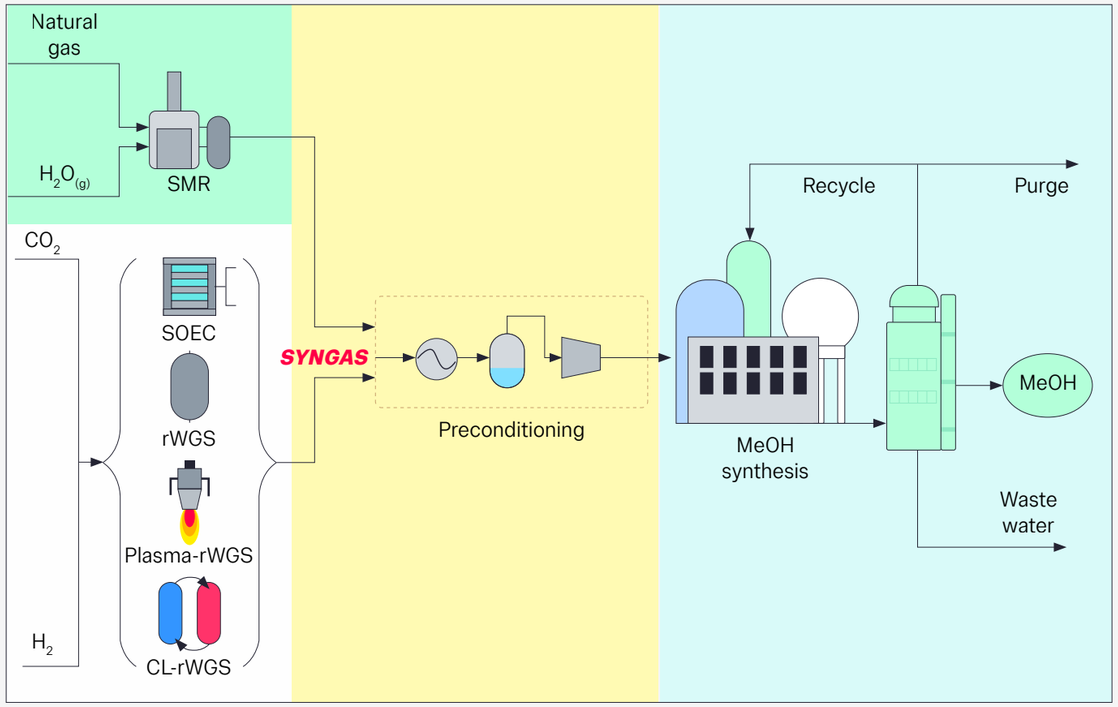

Figure 1. Comparative process pathways for methanol production. The left panel shows the alternative syngas generation routes considered in this study, including the fossil SMR benchmark and the low-carbon CO_2/H_2-based routes. The middle panel represents syngas conditioning before methanol synthesis. The right panel represents the common downstream methanol synthesis and purification section, including recycle, purge, methanol recovery and wastewater removal.

a) Conventional thermocatalytic rWGS: This pathway serves as the technological baseline, utilising a standard Ni/Al2O3 catalyst [30]. The feed section involves the mixing of low-carbon H_2 and captured CO_2 at a stoichiometric ratio of 3 [19]. This mixture is compressed to 10.5 bar and preheated to 560 °C using reactor effluent and subsequently mixed with steam to prevent carbon deposition on the catalyst surface. The reactor operates at 800 °C, a temperature necessitated by the endothermic nature of the reaction. Because the reaction is equilibrium-limited, a 35% recycle of the syngas stream back to the reactor is required to achieve the target module number (M = 2.05).

b) Advanced chemical looping rWGS (CL-rWGS): This pathway adopts a process intensification strategy by utilising a solid oxygen carrier, specifically La0.6Sr0.4FeO3-δ (LSF) pellets, to decouple the rWGS reaction into distinct redox cycles [32,33]. As described in a previous study (Freire et al., under peer review), this configuration utilises a counter-current fixed-bed reactor where the oxygen carrier acts as a chemical intermediate. In the reduction half-cycle, H_2 reduces the LSF carrier at 650 °C to produce steam. In the subsequent oxidation half-cycle, CO_2 reacts with the reduced carrier to yield high-purity CO. This spatial separation allows the process to circumvent the global gas-phase equilibrium constraints, enabling a single-pass CO_2 conversion of 94%. This route eliminates the requirement for syngas recycling.

c) Plasma-assisted rWGS: This route utilises an electrified thermal direct-current (DC) arc reactor to provide the high energy density required for CO_2 dissociation. Based on the framework established by Theofanidis et al. [19], the DC arc generates a high-temperature plasma zone exceeding 1500 °C. At these temperatures, the reaction proceeds through thermal dissociation and radical-mediated pathways rather than traditional catalysis. The reactor is modelled using a Gibbs free energy minimisation approach to achieve a thermal equilibrium conversion of approximately 89.6%. A critical technical feature of this reactor is its thermal management system, which includes a dual-layer refractory lining (silicon carbide and alumina) to protect the reactor shell from the extreme temperatures of the plasma torch.

d) SOEC pathway: This represents a direct electrochemical approach to syngas production [34,35]. The electrolyser operates at high temperature (700 °C), which significantly reduces the electrical energy demand compared to low-temperature electrolysis due to improved thermodynamics and faster electrode kinetics [34,35]. The electrochemical model accounts for the total cell voltage (V) by summing the Nernst potential (E) and the internal losses, including ohmic, activation, and concentration overpotentials [36]. Activation overpotential is modelled via the Butler-Volmer equation to represent voltage losses from charge transfer [37], while concentration overpotential accounts for diffusion resistance within the porous electrodes [38].
The SOEC comprises a solid ceramic electrolyte, specifically 8%-yttria-stabilised zirconia (8YSZ), which conducts oxygen ions (O^{2-}) between the electrodes. The cathode consists of a Ni-YSZ cermet where CO_2 is reduced to CO and oxygen ions, while the anode, typically made of lanthanum strontium cobalt oxide (LSCo), facilitates the formation of pure O2 as a byproduct. The inherent separation of oxygen from the fuel stream within the SOEC architecture simplifies the purification stages prior to the methanol synthesis reactor.

2.1.2. Methanol synthesis and purification loop
Regardless of the production pathway, the conditioned syngas is directed to a standardised methanol synthesis and purification section [31]. To optimise methanol yield and minimise byproduct formation, the syngas entering the synthesis loop must satisfy a specific stoichiometric module number (M). This parameter is defined as the molar flow rate of hydrogen minus the molar flow rate of carbon dioxide, divided by the sum of the molar flow rates of carbon monoxide and carbon dioxide. All four production pathways are designed to deliver a conditioned gas stream with a module number of approximately 2.05 [39].

The common methanol synthesis loop [31] operates at 100 bar and 220 °C over a Cu/ZnO/Al2O3 catalyst, where the high pressure is required to shift the chemical equilibrium toward methanol formation. The loop is centred around a plug flow reactor (PFR) where unreacted gases are separated from the liquid crude methanol and recycled back to the reactor inlet via a recycle compressor to overcome single-pass conversion limits. The crude methanol is subsequently purified through a sequence of flash separators and a multi-stage distillation train to produce high-purity methanol, with a purity above 99%, at approximately 200 t/h, ensuring the effective separation of water and unreacted dissolved gases.

2.2 Economic analysis

The economic viability of each methanol production pathway is evaluated by quantifying the Net Production Cost (NPC) of methanol, which is derived from the Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) associated with the facility. These costs are calculated using the mass and energy flows obtained directly from the Aspen Plus model simulations. The assessment assumes a new-build facility located in the United Kingdom. For standard chemical engineering equipment units, such as heat exchangers, compressors, separators, and pumps, the Purchased Equipment Cost (PC) is determined utilising the correlations established by Sinnott and Towler [40]. In contrast, for specialised units –

including the conventional rWGS reactor [41], the plasma-assisted reactor [19], the CO_2 electrolyser [42], and the methanol synthesis and separation systems [43] – the PC is calculated using a scaling equation that incorporates reference costs, reference capacities, and a scaling factor (D). Specifically, the PC for the CL-rWGS reactor is assumed to be equivalent to that of a conventional rWGS reactor, in line with previous studies indicating that the rWGS unit has a very low capital cost and contributes negligibly to the overall NPC of syngas [44,45].

All costs, including equipment, raw materials, utilities, and labour, are updated to a consistent 2024 basis using appropriate price indices and exchange rates. The Chemical Engineering Plant Cost Index (CEPCI) [46] is applied to all equipment costs, with the CEPCI for 2024 assumed to be 796.2 [46]. Costs for raw materials and utilities are adjusted using the World Bank Commodity Price Data, also known as the Pink Sheet, applying a 2024 energy index of 101.52 for utility updates and a non-energy index of 112.47 for raw material costs [47].

Following the determination of equipment costs, the Fixed Capital Investment (FCI) and the Total Operating Cost (TOC) are estimated according to the guidelines of Albrecht et al. [41]. The FCI encompasses purchased equipment, installation, and other capital requirements for the construction phase, while the TOC includes all operational expenditures such as raw materials, utilities, labour, maintenance, and other indirect costs. The Annualised Capital Cost (ACC) is calculated using a discounted cash flow approach, accounting for an interest rate (i) of 9.70% [48] and a plant lifetime (t) of 30 years [49,50], with an assumed plant availability of 8,322 hours per year [51].

Finally, the Total Annualised Cost (TAC) is calculated by summing the ACC and the TOC, and the NPC of methanol is derived by dividing the TAC by the Annual Production (AP). This NPC, expressed in USD per kg of methanol, serves as the uniform metric for comparison against the incumbent production route via Steam Methane Reforming (SMR) of natural gas, the cost of which is inferred from market prices [52] under an assumed profit margin of 20% [53].

2.3 Uncertainty analysis

To account for the high volatility of emerging feedstock markets and the technical uncertainties inherent in novel production routes, the uncertainty analysis focuses on three principal uncertain factors: the prices of low-carbon (LC) hydrogen, captured CO_2, and industrial electricity, with their respective minimum and maximum boundaries summarised in Table 1.

Component	Minimum	Base case	Maximum
H_2, USD/kg	1.00	4.50	10.20
	White hydrogen [54]	*Blue hydrogen [55]*	*Green hydrogen [55]*
CO_2, USD/kg	0.05	0.60	0.60
	BECCS in biorefineries [7]	*LT (low temperature) DAC [56]*	*LT (low temperature) DAC [56]*
Electricity, USD/MWh	183.9	217.00	321.00
	UK industrial prices of the last three years (excl. Climate Change Levy) [57]		

Table 1. Base case, minimum and maximum price boundaries for the principal uncertain inputs

The term low-carbon (LC) hydrogen is utilised to encompass white, blue and green hydrogen, reflecting the diverse market and technical uncertainties inherent to each route. Specifically, blue hydrogen costs are highly susceptible to natural gas price fluctuations [58], whilst green hydrogen estimates vary based on the intermittency of renewable energy [59], and white hydrogen remains subject to the emerging technical and economic uncertainties of geological extraction [54]. Comparable price uncertainty applies to CO_2, which varies significantly depending on the capture source; for instance, cost estimates fluctuate across a wide spectrum, including bioenergy with carbon capture and storage (BECCS) from biorefineries, concentrated industrial point sources, and direct air capture (DAC) [60]. Additionally, electricity prices exhibit notable volatility driven by the regional grid mix, the increasing penetration of intermittent renewables and local regulatory frameworks [57]. All sampling and analysis routines are implemented in Python using the SALib library [61] for design generation, NumPy [62] for numerical computation, and Pandas [63] for data handling.

The first methodology is a variance-based global sensitivity analysis (GSA), which apportions the variance of the methanol NPC into contributions attributable to the three uncertain prices [64–66]. Efficient coverage of the uncertainty space is ensured via quasi-Monte Carlo sampling with Sobol low-discrepancy sequences, which provide an even spread of points and faster convergence than traditional pseudo-random methods [67–69]. With three inputs (D=3) and a base sample size (N) of 1,024, a total of 8,192 model evaluations are performed per production pathway. Since the prices of LC hydrogen, captured CO_2, and industrial electricity enter separately in the NPC calculations, their impact is expected to be essentially additive here. This is confirmed by the first-order Sobol indices adding to 1, so first-order indices alone are sufficient to fully describe the NPC variance.

Complementing the global analysis, a probabilistic one-at-a-time (OAT) analysis is performed to visualise how individual price uncertainties shape the NPC distribution in isolation. Each uncertain price is described by a Gaussian distribution centred at the midpoint of its defined market range (Table 1), with standard deviation σ such that the full market range corresponds to $\pm 3\sigma$ [40]. For each cost driver, a Monte Carlo experiment consisting of 10,000 iterations is executed. Crucially, while the active variable is sampled across its distribution, the remaining two input parameters are held strictly constant at their designated base case values (as detailed in Table 1).

This dual approach ensures a robust assessment of economic risk and identifies the dominant cost drivers across all evaluated pathways.

3. Results

3.1 Process modelling

A summary of the mass flow rates for the routes studied is provided in Table 2, while the energy flows and utility requirements after heat integration are presented in Table 3.

The conventional rWGS pathway is the most mass-intensive, requiring 377 t/h of CO_2 and 52 t/h of H_2. This high consumption is attributed to the equilibrium limitations of the thermocatalytic reaction and the requirement for excess steam to suppress carbon formation on the catalyst, which leads to a substantial wastewater stream of 457 t/h.

Inputs					Outputs				
	SOEC	rWGS	Plasma-rWGS	CL-rWGS		SOEC	rWGS	Plasma-rWGS	CL-rWGS
Feedstocks	**t/h**	**t/h**	**t/h**	**t/h**	**Product**	**t/h**	**t/h**	**t/h**	**t/h**
CO_2	305	377	296	295	Methanol	197	197	197	197
H_2	31	52	41	41					
H_2O		308		242	**By-products**	**t/h**	**t/h**	**t/h**	**t/h**
					Wastewater	17	457	117	358
					Off-gases	34	83	23	23
					O2	88			
TOTAL	**336**	**737**	**337**	**578**	**TOTAL**	**336**	**737**	**337**	**578**

Table 2. Mass flow rates for the studied routes at approximately 200 t/h methanol. Values are rounded to the nearest tonne per hour.

In contrast, the CL-rWGS and Plasma-rWGS routes demonstrate higher carbon utilisation, requiring about 295 t/h of CO_2. The CL-rWGS pathway achieves this by decoupling the reaction into redox cycles, circumventing gas-phase equilibrium and eliminating the need for syngas recycling. The SOEC pathway exhibits the lowest H_2 demand (31 t/h) because it produces CO via the direct electrochemical reduction of CO_2 at the cathode, while simultaneously producing a high-purity O2 byproduct (88 t/h) at the anode.

		SOEC	rWGS	Plasma-rWGS	CL-rWGS
Utilities		***MW***	***MW***	***MW***	***MW***
Electricity		777	278	362	142
Heating utilities	HP steam/Fired heater (NG, eff. 90%)	445	398	253	398
Cooling utilities	Cooling water	374	567	413	389

Table 3. Energy flow rates after heat integration for the studied routes at approximately 200 t/h methanol. Values are rounded for readability.

The SOEC pathway is significantly more electricity-intensive than the other routes, requiring 777 MW. This is due to the substantial electrical work required to overcome the Nernst potential and internal overpotentials (ohmic, activation and concentration) during the high-temperature electrolysis of CO_2.

The Plasma-rWGS route requires the lowest heating utility (253 MW) because the electrified DC arc provides the high energy density needed for thermal dissociation directly within the plasma zone. Conversely, the conventional rWGS pathway has the highest cooling demand (567 MW), primarily necessitated by the cooling and condensation of the large quantities of excess steam used in the feed section. The CL-rWGS pathway presents the lowest overall electricity demand (142 MW), as it avoids both the high-voltage requirements of electrolysis and the plasma arc power consumption.

3.2 Economic analysis

The economic evaluation of the four pathways is primarily measured by their NPC, which integrates both capital and operating expenses into a single performance metric. As shown in Figure 2, the chemical looping (CL-rWGS) route is the most competitive in the base-case analysis, yielding an NPC of 2.17 USD/kg methanol, followed by plasma-rWGS at 2.47 USD/kg methanol. The conventional rWGS and SOEC pathways exhibit higher base-case costs of 3.13 USD/kg methanol and 3.63 USD/kg methanol, respectively. Since the unit prices for raw materials and utilities remain constant across all models, these disparities are entirely reflective of the process efficiencies and consumption rates inherent to each technology.

Analysis of the broad cost structure reveals that OPEX, particularly feedstock and utility procurement, is the dominant contributor to the NPC for every pathway. CAPEX remains a secondary factor, although it exerts a more noticeable influence on the SOEC route than on the thermocatalytic or plasma-based alternatives. The high share of variable costs underscores that the economic viability of these syngas-to-methanol pathways is fundamentally tied to the efficiency of the syngas production stage – specifically how effectively carbon dioxide and hydrogen are converted – alongside the intensity of electricity consumption.

The competitive advantage of the CL-rWGS and Plasma-rWGS routes stems from their superior feedstock utilisation and moderate electricity demand. In contrast, the conventional rWGS pathway is heavily penalised by its high consumption of both carbon dioxide and low-carbon hydrogen, which represent its primary cost drivers. Meanwhile, the SOEC pathway is constrained by the significant electrical power required for the electrochemical reduction of carbon dioxide and a higher capital burden compared to the other routes. Whilst the SOEC process benefits from the lowest hydrogen consumption in the group, these savings are currently outweighed by the substantial electrical and capital premiums associated with the technology.

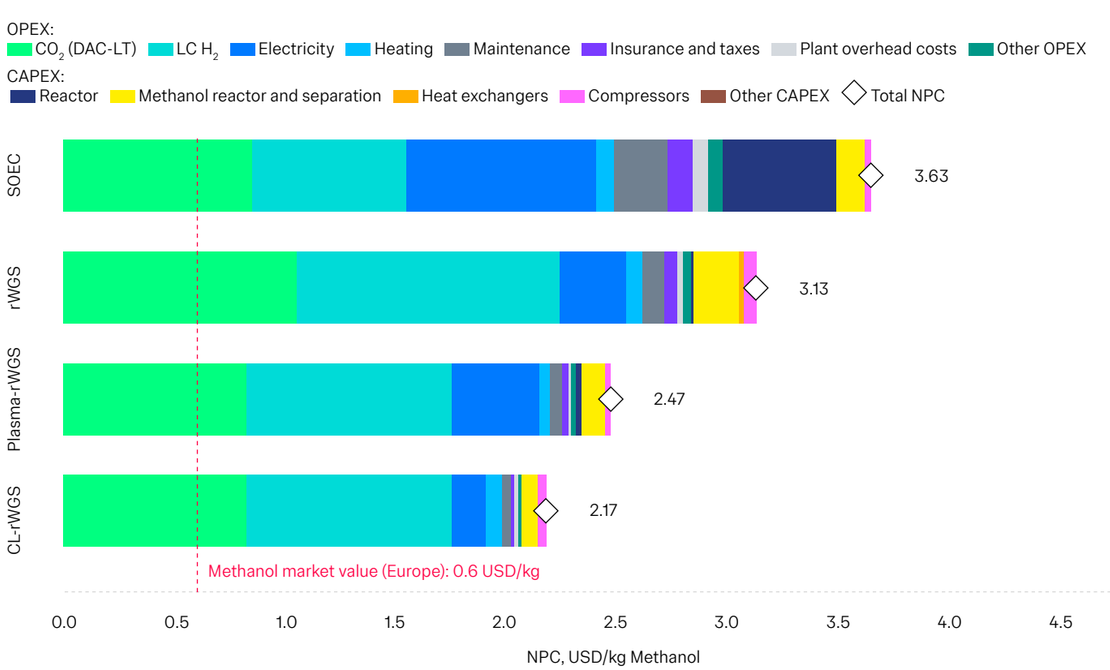

Figure 2. Comparative NPC breakdown for the SOEC, rWGS, plasma-rWGS and CL-rWGS pathways. Operating expenditures (OPEX) and capital expenditures (CAPEX) are distinguished in the legend. The total NPC marker represents the sum of all OPEX and annualised CAPEX contributions.

3.3 Economic sensitivity to price uncertainty

The uncertainty analysis provides a robust probabilistic assessment of the economic resilience of the four syngas production routes by propagating uncertainty in low-carbon hydrogen, captured CO_2 and industrial electricity prices around the base-case economic framework presented in Section 3.2. As illustrated in Figure 3 and the corresponding statistical results, the CL-rWGS pathway demonstrates the highest economic competitiveness under joint price uncertainty, maintaining the lowest mean and median NPC at 2.09 USD/kg methanol. This is followed by the plasma-rWGS route with a mean of 2.43 USD/kg methanol, while the conventional rWGS and SOEC pathways are significantly less competitive, with mean costs of 3.04 USD/kg methanol and 3.61 USD/kg methanol, respectively. The near-zero skewness across all datasets indicates that the cost distributions are highly symmetric, suggesting that these mean values are reliable indicators of the expected economic performance in real-world scenarios.

A critical finding from this analysis is the varying degree of sensitivity to market volatility exhibited by each technology. The conventional rWGS pathway is identified as the most financially volatile option, yielding the highest standard deviation of 0.76 USD/kg methanol and the widest total range of 3.52 USD/kg methanol; this is because rWGS consumes the largest amounts of LC hydrogen and captured CO_2, thus reflecting their uncertain market prices on the predicted NPC. In contrast, the SOEC pathway appears less sensitive to market price uncertainty, with the lowest standard deviation of 0.51 USD/kg methanol, as it consumes much lower amounts of LC hydrogen. However, even in the most optimistic market scenarios, the minimum NPC of 2.26 USD/kg methanol remains higher than the mean performance of the CL-rWGS pathway, effectively ruling out the SOEC pathway due to a lack of economic competitiveness under the tested conditions.

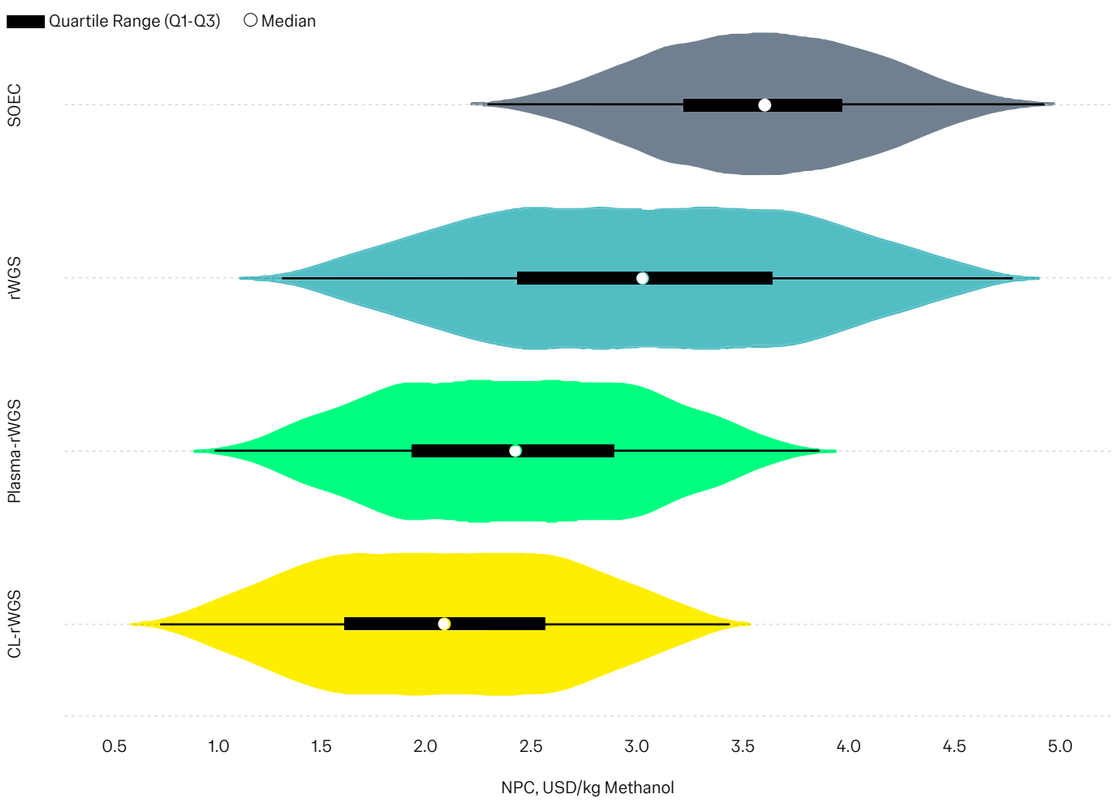

Figure 3. Comparative NPC distributions for the SOEC, rWGS, plasma-rWGS, and CL-rWGS pathways under joint uncertainty propagation. The distributions are generated assuming statistical independence between the sourcing prices of electricity, H_2, and CO_2. Crucially, the industrial electricity parameter varied here corresponds strictly to the power consumed within the chemical plant boundaries to synthesise methanol, rather than the energy required for upstream feedstock production or capture. Within the scope of this study, both H_2 and CO_2 are treated as external merchant feedstocks, directly purchased from suppliers rather than generated or captured on-site.

The OAT sensitivity analysis identifies the low-carbon H_2 price as the primary economic driver across all four production pathways, as illustrated in Figure 4. The conventional rWGS route exhibits the highest sensitivity to H_2 price volatility, with the NPC ranging from 1.78 to 4.94 USD/kg methanol. The plasma-rWGS and CL-rWGS pathways follow, with ranges of 1.42–3.88 USD/kg and 1.27–3.52 USD/kg methanol, respectively. In contrast, the SOEC pathway is the least sensitive to H_2 price fluctuations, with costs varying between 2.95 and 4.67 USD/kg methanol. Despite these varying degrees of sensitivity, the consistently wide distribution for H_2 across all models confirms that the economic feasibility of low-carbon methanol is fundamentally tethered to the future cost reduction of low-carbon hydrogen.

Secondary and tertiary drivers follow a uniform hierarchy across the pathways, with the CO_2 price exerting the next greatest influence, followed by the price of electricity. While the SOEC route displays a notably higher sensitivity to electricity costs (3.42–4.14 USD/kg methanol) compared to the rWGS, plasma-rWGS, and CL-rWGS pathways, this impact remains secondary to feedstock costs. It is notable that the CL-rWGS route maintains the lowest cost profile throughout the analysis, as its upper range for CO_2 and electricity sensitivities remains significantly below the base-case NPC of the other three pathways. These results demonstrate that while market volatility affects every technology, the chemical looping and plasma-based processes provide a more resilient baseline against price fluctuations in raw materials and electricity.

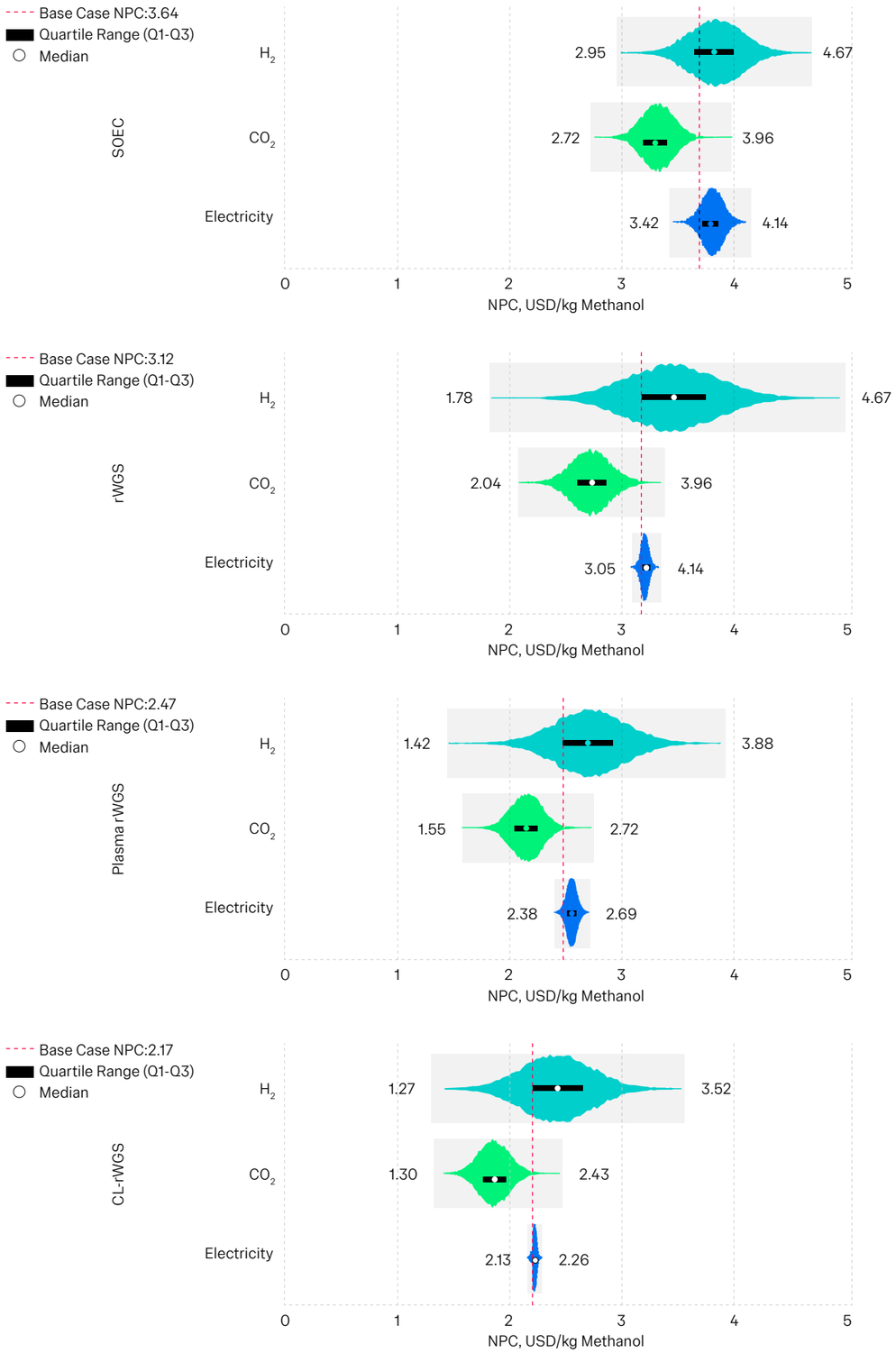

Figure 4. Comparative NPC sensitivity for the SOEC, rWGS, plasma-rWGS and CL-rWGS pathways under OAT analysis. Base-case NPC values and sensitivity ranges are reported in USD/kg methanol and displayed to two decimal places.

4. Cost-reduction pathways for sustainable methanol production

Following the TEA and associated sensitivity analyses, the CL-rWGS route was identified as the most promising pathway for producing sustainable methanol in the present study. The economic viability of this pathway remains highly dependent on the specific origin of the low-carbon hydrogen feedstock. While green (electrolytic) and blue (fossil-derived with carbon capture) hydrogen currently impose substantial economic premiums, naturally occurring geologic “white” hydrogen provides a uniquely low-cost alternative. Under the baseline assumptions, this route yields the lowest estimated NPC, at 0.68 USD/kg methanol, when supplied with this white hydrogen and captured biogenic CO_2 from BECCS in biorefineries. The baseline NPC breakdown shows that the main cost drivers are white hydrogen, contributing 0.21 USD/kg methanol, industrial electricity, contributing 0.13 USD/kg methanol, and BECCS-derived CO_2, contributing 0.07 USD/kg methanol, while the remaining CAPEX and OPEX items together account for 0.27 USD/kg methanol. This cost structure shows that the strongest leverage for further reducing methanol production cost lies in lowering the costs of hydrogen, electricity and CO_2 supply.

The wider literature on renewable fuels, hydrogen systems and carbon management consistently identifies hydrogen cost, electricity price and carbon feedstock cost as major drivers for the production cost [70–72]. On this basis, a cascade analysis (Figure 5) examines how literature-based improvements in these three drivers would translate into reductions in methanol NPC for the CL-rWGS route, focusing on cost reductions associated with the key factors identified by the TEA.

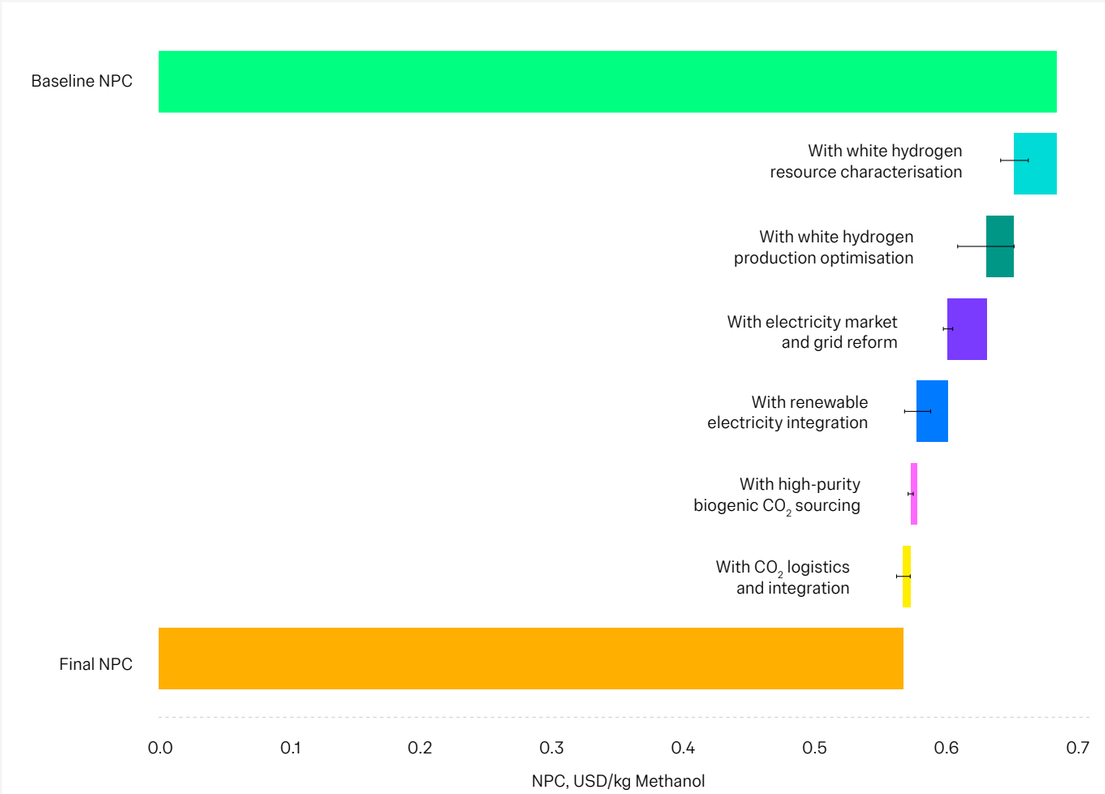

Figure 5. Reduction in methanol NPC achieved through different cost-reduction levers for the CL-rWGS route. The solid-coloured bars indicate the central case, and the black lines indicate the maximum and minimum reductions based on the literature ranges considered. The baseline bar represents the initial NPC of methanol, equal to 0.68 USD/kg methanol, and the final bar represents the central-case net production cost after the sequential application of the cost-reduction levers, equal to approximately 0.57 USD/kg methanol.

Among the three drivers, industrial electricity presents the clearest opportunity for cost reduction. IRENA [70] reports global weighted-average levelised electricity costs in 2024 of approximately 34 USD/MWh for newly commissioned onshore wind and 43 USD/MWh for utility-scale solar photovoltaics. In industrial applications, the delivered electricity cost depends not only on generation cost, but also on network charges, market access, contractual arrangements, balancing requirements and operational flexibility. The UK Government [73] has indicated that electricity-intensive manufacturers could reduce electricity bills by up to 25% through reforms to levies and network charges. Additional reductions may be achieved through renewable power purchase agreements, co-location with generation, storage deployment and flexible operation, all of which are widely discussed in the literature on industrial decarbonisation and electrolytic hydrogen production [70,72]. In the present analysis (Figure 5), electricity cost reduction is split in two stages. The first stage consists of tariff, levy and grid-access improvements, corresponding to a 20-25% reduction in electricity cost. The second stage consists of renewable electricity procurement, co-location, storage and flexible operation, increasing the total reduction to 35-45% relative to the baseline case.

The second major cost-reduction pathway is white hydrogen. Recent reviews identify the main constraints on white hydrogen development as exploration uncertainty, prospectivity assessment, reservoir characterisation, drilling and completion in suitable geological formations, gas purification, and integration with transport infrastructure [74,75]. The emerging literature suggests that white hydrogen production costs may be around 1.0 USD/kg, with lower values potentially achievable in favourable geological settings [75]. In the present analysis, the hydrogen cost reduction pathway is again split in two stages. The first stage consists of improved exploration, prospectivity mapping and reservoir appraisal, corresponding to a 10-20% reduction in hydrogen cost. The second stage consists of drilling optimisation, purification improvements and integrated production systems, increasing the total reduction to 20-30% relative to the baseline. Applied to the methanol cost structure, this indicates that the hydrogen-related contribution to methanol NPC could be reduced materially if geological risk is lowered and field productivity is improved.

The third cost-reduction pathway is BECCS-derived CO_2 from biorefineries. In the baseline case, this stream is already relatively low-cost at 50 USD/t CO_2. The literature indicates that some of the most favourable opportunities for BECCS arise in fermentation-based biorefineries because fermentation off-gas is typically above 98% CO_2 by volume and therefore requires limited upgrading prior to use or storage [71]. For these streams, the main technical and economic issues are compression, dehydration, purification, transport and source-sink integration. European assessments of BECCS deployment also emphasise the importance of transport distance, access to shared infrastructure and regional storage availability [76]. Since the baseline value already represents a relatively favourable CO_2 supply case, the scope for further reduction is more limited than for electricity and hydrogen. In the present analysis, CO_2 cost reduction is once more split in two stages. The first stage consists of prioritising high-purity fermentation streams and optimising compression and purification, corresponding to a 5-10% reduction in CO_2 cost. The second stage consists of shared transport and storage infrastructure, favourable siting and process integration, increasing the total reduction to 10-20% relative to the baseline.

Using the midpoint values of the literature-based reduction ranges, the methanol NPC decreases from 0.68 to 0.57 USD/kg methanol. The largest reduction potential is associated with electricity and white hydrogen, whereas the contribution from BECCS-derived CO_2 is smaller because the baseline CO_2 cost is already relatively low. The main priorities are therefore to reduce industrial electricity cost through grid, tariff and renewable procurement measures, to improve white hydrogen supply through exploration and production optimisation, and to lower the delivered cost of biogenic CO_2 through source selection and transport integration. The supporting evidence is strongest for electricity and BECCS-derived CO_2, while white hydrogen remains more uncertain as commercial-scale geological performance is not yet well established.

5. Conclusion

This study evaluated the economic viability and resilience of diverse syngas production pathways for sustainable methanol synthesis, focusing on identifying the primary hurdles to displacing conventional fossil-based production. By employing rigorous process modelling and global sensitivity analysis, the research sought to uncover the specific technological and market conditions required for low-carbon pathways to achieve economic parity within industrial sectors.

The uncertainty analysis identifies advanced chemical looping (CL-rWGS) as the most economically competitive pathway for syngas generation, yielding the lowest mean NPC under price uncertainty of 2.09 USD/kg methanol, followed by the plasma-rWGS route at 2.43 USD/kg methanol. In contrast, the conventional rWGS and SOEC-based electrolysis pathways demonstrate considerably lower competitiveness, with mean NPC values of 3.04 USD/kg methanol and 3.61 USD/kg methanol, respectively. To contextualise these economic figures within a sustainability framework, a preliminary Life Cycle Analysis (LCA) was conducted using Simapro v9.0 and Ecoinvent 3.5. Under the idealised assumption that both the hydrogen feedstock and electricity are sourced from zero-carbon origins, and utilising low-temperature DAC as the CO_2 source, the Global Warming Potential (GWP) of methanol was estimated at -0.22, -0.41, -0.26, and -0.09 kg CO_2-eq/kg for CL-rWGS, plasma-rWGS, rWGS, and SOEC, respectively. These results contrast sharply with the fossil-based baseline (BAU) GWP of 0.66 kg CO_2-eq/kg, illustrating the significant decarbonisation potential of these routes if fully sustainable inputs are secured.

This environmental advantage, however, is tethered to a substantial economic premium. By integrating the economic and environmental findings, the Carbon Abatement Cost (CAC) relative to the natural gas-derived methanol market value of 0.60 USD/kg is calculated at 1,702 USD/t CO_2 for CL-rWGS and 1,709 USD/t CO_2 for plasma-rWGS. The abatement costs for conventional rWGS and SOEC are even higher, at 2,657 USD/t CO_2 and 4,012 USD/t CO_2, respectively. These figures underscore the substantial economic “green” premium required to achieve such environmental benefits, even when assuming a fully decarbonised energy and feedstock supply.

A detailed breakdown of the NPC results indicates that CAPEX represents a small fraction of the total cost compared to the OPEX, which is overwhelmingly dominated by the procurement costs of low-carbon hydrogen, captured CO_2, and electricity. The sensitivity analysis further confirms that achieving cost parity with the fossil-based BAU benchmark of 0.60 USD/kg is remarkably difficult. In this regard, the targeted cascade analysis indicates a prospective trajectory of supply-chain advancements that could allow the leading CL-rWGS configuration to bridge the gap to market competitiveness. While utilising white hydrogen and biogenic CO_2 from BECCS compresses the initial methanol NPC to 0.68 USD/kg, this baseline configuration remains uncompetitive against the 0.60 USD/kg conventional fossil benchmark. Within this initial layout, white hydrogen contributes 0.21 USD/kg, industrial electricity 0.13 USD/kg, and biogenic CO_2 0.07 USD/kg, with the remaining CAPEX and OPEX items accounting for 0.27 USD/kg. Market competitiveness is shown to be conditional upon sequentially layering literature-backed supply-chain improvements, which compress the central-case NPC further to 0.57 USD/kg, potentially positioning the process within proximity of parity with the fossil baseline. This projected reduction is enabled mainly by electricity tariff reforms and renewable co-location, advanced mapping and drilling optimisations for white hydrogen, and integrated biogenic CO_2 transport networks.

Consequently, these insights indicate that a fundamental shift in research and deployment priorities is required; rather than focusing on plant capital cost mitigation, future efforts must target aggressive process intensification and volumetric feedstock reduction per unit of product. To address these structural challenges, the subsequent section provides a comprehensive outlook on the specific technological innovations, supply-chain integrations, and policy mechanisms essential to facilitate this transition and secure a sustainable methanol economy.

6. Outlook: Technological innovation and policy drivers

6.1 Process intensification

Technological breakthroughs in syngas conversion are essential to facilitate the industrial transition from conventional fossil-based production to sustainable, low-carbon methanol synthesis pathways. Future research must prioritise the development of next-generation catalysts designed to achieve a methanol selectivity in excess of 95% while operating at lower temperatures between 220°C and 240°C [77,78]. Such innovations are vital for improving single-pass conversion rates, thereby restricting the volume of H_2 and CO_2 required by limiting the energy-intensive recycling of unconverted syngas [78].

Concurrently, transitioning from conventional configurations to multi-stage adiabatic reactors with optimised inter-cooling, or isothermal reactors with internal cooling, is necessary to manage exothermic heat release more effectively and maintain optimal temperature profiles [79,80]. Advanced reactor intensification – including the deployment of membrane reactors or physically mixed bifunctional catalyst systems – offers a promising route to enhance single-pass CO_2 conversions. This would significantly lower the compression and recycling penalties that currently drive the high NPC of e-methanol [77–79].

6.2 System-wide energy integration

Beyond reactor design, system-wide efficiency must be enhanced through comprehensive heat recovery networks and advanced process coupling [81,82]. Implementing these networks can improve overall thermal efficiency by 15–25% by capturing high-temperature reaction heat from the synthesis stage and routing it to regenerate CO_2 capture solvents or for feed preheating [81].

On the feedstock supply side, shifting focus toward proton-conducting high-temperature electrolysers and the direct co-electrolysis of CO_2 and H_2O represents a critical frontier. R&D in high-power stack development aims to elevate electrical-to-methanol efficiencies to a target range of 65–75%, directly tackling the industrial electricity consumption penalty that dictates the baseline economics of electrified pathways [83,84].

6.3 Transitional frameworks and policy mechanisms

As a pragmatic near-term measure, the integration of low-carbon hydrogen into existing natural gas-based infrastructure – via feedstock blending – should be explored to drive down immediate carbon intensity while utilising established industrial assets [85,86]. This transition can be commercially de-risked through modular capacity expansion, enabling incremental deployment that facilitates iterative technology refinement, “learning-by-doing”, and the mitigation of capital risk prior to full-scale commercialisation [87].

Ultimately, the remaining economic divide must be bridged by robust policy mechanisms. Long-term Contracts for Difference (CfDs) and targeted carbon pricing or taxation are vital to provide revenue certainty for these high-OPEX facilities [87–89]. Furthermore, enforcing strict mandates for renewable fuels of non-biological origin (RFNBOs) within the maritime and aviation sectors will be instrumental in anchoring a guaranteed market for sustainable methanol [87,88].

6.4 Supply chain realities and life cycle constraints

All such economic and technical strategies must be guided by rigorous Life Cycle Analysis (LCA) to ensure that process optimisations remain authentically aligned with genuine climate neutrality targets [87,90]. Given that the environmental benefits established in the preceding conclusions are predicated upon an idealised scenario of strictly zero-carbon energy and hydrogen feedstocks, a comprehensive LCA is mandatory to accurately quantify environmental impacts based on the real feedstocks and utilities employed in current practice.

Such evaluations are essential to move beyond the theoretical potential identified in this study and identify actual environmental hotspots – most notably the carbon intensity of the marginal electricity mix – thereby preventing the unintended shifting of burdens across the supply chain. By ensuring that assessments reflect the practical constraints of real-world infrastructure, the transition to sustainable methanol can be secured as both economically resilient and environmentally robust [89,90].

6.5 Downstream applications: The methanol-to-jet competitiveness gap

To illustrate the economic challenge associated with downstream fuel applications, a competitiveness screening can be applied to methanol-based aviation fuels. Because the viability of this route is highly sensitive to the volatile market price of conventional aviation fuel, the break-even threshold for sustainable methanol fluctuates accordingly. Using the methanol-to-olefins (MTO) and Mobil’s Olefins to Gasoline and Distillate (MOGD) process configuration reported by Ruokonen et al. [91], the pathway was evaluated on a netback basis. Crucially, this assumes the economic value of all useful co-products – which in this specific MTO-MOGD configuration are explicitly upgraded to green gasoline, diesel, LPG, and surplus steam – is credited directly back to the process to offset the cost burden of the kerosene fraction. Given the historical volatility of U.S. Gulf Coast kerosene-type jet fuel spot prices, which have fluctuated broadly between approximately 2.00 and 4.50 USD/gal in recent years [92], the required methanol transfer price for the kerosene fraction to achieve market parity is estimated to range correspondingly from 0.05 to 0.14 USD/kg.

The competitiveness threshold is nevertheless very low. It implies that, under current fossil jet prices, methanol-to-jet pathways are highly exposed to the cost of upstream methanol production. This outcome is consistent with the broader techno-economic findings of Ruokonen et al. [91], who identify methanol cost as the main driver of total production cost in the MTO-MOGD route. Since methanol in turn depends strongly on the cost of low-carbon hydrogen, renewable electricity, and carbon feedstock provision, the downstream aviation-fuel application effectively amplifies cost pressures originating earlier in the value chain. As a result, even moderate deviations in methanol production cost can lead to large changes in the final competitiveness of the kerosene fraction.

Although this estimate is intentionally simplified and bound to the specific architectural assumptions of the underlying model, it serves as a valuable order-of-magnitude indicator. It demonstrates that methanol-to-jet pathways are exceptionally sensitive to upstream synthesis costs, making them unlikely to achieve unsubsidised market competitiveness unless sustainable methanol production costs fall substantially via the R&D breakthroughs detailed above, or aggressive policy mechanisms directly subsidise the green premium.

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Please cite:

Freire Ordonez, D, Chachuat B,Shah N, (2026) Sustainable Methanol Production via Syngas-Mediated Pathways: A Techno-Economic Comparison.

DOI: https://doi.org/10.25560/131602