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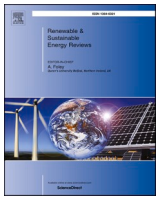

Not all CO_2 is equal: Source-specific constraints and viability trade-offs in methanol synthesis from industrial emissions

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ABSTRACT

Methanol synthesis from captured CO_2 is widely regarded as a promising pathway for carbon utilization, yet its feasibility depends heavily on the characteristics and constraints of the CO_2 source. This review evaluates four industrial point sources—biogas, steel plants, cement kilns, and waste-to-energy facilities—highlighting key differences in CO_2 purity, contaminant load, hydrogen integration, and catalyst stability. We propose a five-axis viability framework, developed through a synthesis of current literature, to structure source-specific comparison and guide system-level evaluation. The framework includes CO_2 usability, hydrogen vulnerability, contaminant burden, integration potential, and policy exposure. By applying this structured lens, the review identifies key performance-limiting trade-offs, techno-economic constraints, and integration barriers across point sources. Results show that biogas and steel off-gases offer favourable trade-offs (scores of 15–18/25), while cement and waste-to-energy streams face major integration and degradation challenges ($\leq$9/25). Reforming pathways, gas conditioning requirements and modular deployment considerations are also discussed. This review concludes that effective CO_2-to-methanol deployment requires source-specific process design, improved contaminant-tolerant catalysts, and better alignment of infrastructure and policy to the heterogeneous nature of industrial CO_2 sources.

1. Introduction

The synthesis of methanol from captured carbon dioxide (CO_2) has emerged as a key strategy for advancing circular carbon systems and mitigating greenhouse gas emissions [1,2]. Methanol functions both as a platform chemical and as an energy carrier, enabling its integration into existing industrial and energy infrastructures. While traditional methanol production relies on syngas derived from fossil feedstocks, attention has shifted toward the catalytic hydrogenation of CO_2 using renewable hydrogen as a cleaner, more sustainable route CO_2 [3,4].

However, despite notable advances in catalyst development and reactor optimization, the feasibility of upscaling CO_2-to-methanol conversion hinges not only on process-level parameters but on the characteristics of the CO_2 and H_2 sources [5]. This includes variables such as CO_2 concentration, impurity burden, thermal profile, and spatial-temporal availability. Yet, a large portion of the literature treats CO_2 as a fungible, homogeneous input—detached from its industrial origin and divorced from the logistics of capture, purification, and integration [6,7]. This treatment extends to other key subsystems as well, such as hydrogen and catalyst systems, which are often modelled under idealized or static assumptions. For CO_2, important distinctions persist: biogas-derived CO_2 may contain siloxanes and H_2S, while steel off-gases carry tars and heavy metals CO_2 [8–10]. Similarly, cement kiln exhausts and waste-to-energy (WtE) flue gases differ widely in CO_2 content and co-stream reformability [11,12]. Such heterogeneity cascades through system design, influencing hydrogen demand, catalyst tolerance, reforming compatibility, and ultimately the techno-economic viability of methanol production. Still, many feasibility studies operate within idealized system boundaries that neglect these upstream constraints [13–15]. The result is a growing mismatch between the theoretical feasibility of CO_2 utilization technologies and their deployability in source-specific industrial contexts.

To assess the viability of CO_2-to-methanol production, researchers have traditionally relied on frameworks such as Life Cycle Assessment

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(LCA), Techno-Economic Assessment (TEA), and Multi-Criteria Decision Analysis (MCDA). While these tools provide important environmental and economic benchmarks, they often fail to incorporate the heterogeneity of CO_2 and H_2 streams, infrastructure compatibility, or policy fragmentation—especially in decentralized applications [16–18]. Recent reviews have further expanded on catalyst families and process innovations [5,14,19], but few provide a framework that systematically connects source variability, hydrogen infrastructure, and catalytic resilience to overall methanol synthesis viability.

In response, the present review introduces a new evaluative framework that explicitly links CO_2 source characteristics to methanol synthesis viability. The study pursues two main objectives. First, in Section 2, we present a critical review of existing feasibility assessment methodologies, clarifying how current LCA-, TEA-, and MCDA-based approaches neglect source-specific variability, integration barriers, and exposure to policy risk. Second, in Section 3, we introduce a novel five-axis viability framework designed to evaluate methanol production potential across diverse industrial CO_2 sources using five distinct dimensions: CO_2-Usability Potential (CUP), Hydrogen Vulnerability Index (HVI), Contaminant Load Factor (CLF), Integration Complexity Score (ICS), and Policy Risk Exposure (PRE). The framework is subsequently applied to four representative industrial CO_2 sources: biogas, steelworks, cement kilns and WtE facilities and conceptually extended to hydrogen and catalyst subsystems to illustrate cross-domain applicability. These sources were selected for their global relevance, varying contaminant profiles, and strategic implications for carbon valorization. By integrating subsystem interactions into a unified viability model, this review emphasizes that successful CO_2-to-methanol deployment depends on coordinated, source-responsive process design. Ultimately, by linking upstream CO_2 and H_2 characteristics, catalyst tolerance, and integration complexity to downstream viability, this supports more grounded and context-aware decision-making in methanol synthesis.

2. Systematic review of CO_2-to-methanol assessment frameworks

The feasibility of CO_2-to-methanol synthesis has garnered extensive attention in recent years as part of broader efforts to decarbonize industrial sectors. Researchers have applied a wide array of analytical tools—including LCA, TEA, system-level modelling, and (MCDA—to evaluate its environmental, economic, and technical viability [14,15,20,21]. Several review papers have summarized progress in catalyst development, process intensification, or methanol market integration; however, few have systematically compared the assessment frameworks themselves, or critically examined how these methods incorporate source-specific constraints such as CO_2 purity, contaminant burdens, hydrogen logistics, and policy context [22,23].

This section addresses that gap by reviewing and evaluating the methodological scope, assumptions, and blind spots of major feasibility frameworks used in the CO_2-to-methanol domain. Our analysis highlights that while existing approaches offer important benchmarking functions, they often abstract CO_2 from its industrial origin—overlooking critical upstream constraints that directly affect viability. By synthesizing this literature, we lay the foundation for the five-axis viability framework introduced in Section 3, which seeks to address these oversights through a structured, source-responsive approach.

2.1. Life cycle and techno-economic assessments: strengths and blind spots

LCA has served as a foundational tool in evaluating the environmental performance of CO_2-to-methanol systems. It enables comparative benchmarking of greenhouse gas (GHG) emissions, energy balances, and broader environmental burdens across cradle-to-gate or cradle-to-grave system boundaries [14,24]. LCA studies have been instrumental in identifying environmental hotspots, estimating net CO_2 reduction potential, and exploring the impact of process configurations and energy inputs [15]. However, LCA applications in CO_2 utilization often rely on highly idealized system boundaries and generalized feedstock assumptions. In most studies, CO_2 is modelled as a homogeneous, fully purified input—abstracted from the specifics of its industrial source, capture pathway, or contaminant burden [25]. For instance, Kamolov et al. [26] assume high capture efficiency and omit the energy and emissions associated with multistage gas compression, dehydration, and contaminant removal—steps that are unavoidable for CO_2 derived from biogas, steel, cement, or WtE flue gases. These omissions lead to significant underestimation of upstream burdens in systems where raw CO_2 streams can contain 10–500 ppm sulfur compounds, siloxanes, chlorides, alkali metals, and tars. Because such contaminants directly affect catalyst lifetime and hydrogen demand (via required pre-reforming adjustments), the simplifying assumptions in these studies obscure the real source-dependent penalties that this review seeks to evaluate.

A further limitation arises from inconsistent boundary definitions. As Honegger and Reiner [18] note, variations in LCA scope and assumptions, such as whether electricity for hydrogen electrolysis is grid-based or renewable, or whether upstream emissions from catalyst production are included, complicate cross-study comparisons. This inconsistency is especially problematic in early-stage or small-scale deployments, where the environmental profile is highly sensitive to local integration choices and feedstock conditioning needs. Moreover, LCAs often overlook the operational burdens associated with contaminant removal, an issue particularly relevant for biogas, cement kiln dust, steel off-gas, and WtE, where siloxanes, halides, sulfur species, or heavy metals require intensive pre-treatment. [27–29]. Excluding these penalties can lead to systematic overestimation of environmental performance when applied to real world, source-specific methanol synthesis.

Overall, while LCA provides critical insights into environmental trade-offs, it is not well suited for assessing the viability of methanol synthesis across diverse CO_2 sources [30,31]. Its inability to account for upstream variability and capture-related burdens limits its relevance in evaluating site-specific feasibility. These shortcomings underscore the need for assessment frameworks that embed source-specific constraints, a topic explored later in this review.

2.2. Techno-economic assessments: analytical rigor, operational gaps

TEA is a widely used framework for evaluating the financial feasibility of CO_2-to-methanol synthesis [20,21]. It provides estimates of capital expenditure (CAPEX), operating costs (OPEX), payback periods, and levelized production costs—offering a quantitative basis for investment decisions, technology comparison, and scale-up analysis [14]. In particular, TEA is effective in identifying cost drivers, evaluating the economic impact of process integration, and testing sensitivity to key variables such as electricity price, electrolyzer efficiency, or CO_2 conversion rate [20]. However, like LCA, most TEA models adopt idealized assumptions that limit their utility in source-specific evaluations. Many studies assume constant feedstock purity, seamless hydrogen availability, and fully integrated systems [32–34]. However, these conditions rarely exist outside controlled pilot environments [16,17,35]. For example, Pérez-Fortes et al. and Kätelhön et al. [16,17] model methanol synthesis from CO_2 under the assumption of green hydrogen availability at fixed prices, neglecting real-world variations in hydrogen sourcing strategies, transportation costs, and grid carbon intensity. These simplifications reduce TEA's ability to inform deployment decisions in regions where hydrogen logistics remain unresolved.

Further, TEAs often treat CO_2 as a fungible commodity—neglecting differences in concentration, contaminant load, and required purification steps. While studies such as Artz et al. [19] acknowledge the sensitivity of methanol cost to CO_2 and H_2 input characteristics, they typically generalize across sources or omit pre-treatment costs entirely. This is particularly problematic for emitters like WtE plants, cement kilns, or biogas digesters, where CO_2 stream impurities can significantly raise operational and maintenance costs. The omission of gas cleaning

costs, catalyst poisoning risks, and system downtime in TEA models creates an overly optimistic picture of economic feasibility.

Location-specific variables, such as proximity to hydrogen supply, access to low-carbon electricity, availability of waste heat, and land or permitting constraints, are also rarely embedded into TEA structures [36,37]. This is despite their central role in shaping investment outcomes. A plant co-located with a renewable hydrogen hub may enjoy cost and integration advantages that are completely absent in remote or infrastructure-poor locations. By omitting such spatial and infrastructural realities, TEA results often fail to support grounded, site-specific deployment decisions.

Finally, TEA typically models steady-state, large-scale operations, which may not reflect the intermittency, modularity, or risk profile of smaller, distributed systems [38]. Decentralized methanol production, especially when targeting emerging or hard-to-abate sectors, may face steep cost premiums due to scale limitations, irregular CO_2 supply, or constrained policy support [39]. These dimensions are rarely addressed in conventional TEA models. In summary, while TEA contributes valuable financial insights and cost benchmarks, its reliance on generalized inputs, exclusion of upstream burdens and limited spatial resolution constrain its relevance for evaluating real-world deployment potential. A more integrative approach is needed, one that embeds source characteristics, contaminant risks, and infrastructure constraints into economic feasibility analysis. The five-axis framework introduced in this review offers a step toward such operational granularity.

2.3. System-level modelling and Multi-Criteria Decision Analysis (MCDA): toward complexity, yet still abstracted

In response to the rigid assumptions embedded in traditional LCA and TEA models, a growing body of literature has turned to system-level modelling tools that aim to capture the inherent complexity and uncertainty of CO_2-to-methanol synthesis [14]. These include Monte Carlo simulations, scenario-based planning, and Multi-Criteria Decision Analysis (MCDA)—frameworks that offer more flexible, integrative approaches to feasibility assessment [40]. Such tools are particularly valuable in evaluating trade-offs between economic, environmental, and operational metrics, especially under variable policy, market, or infrastructure conditions [41–44].

Monte Carlo-based methods have enhanced techno-economic assessments by introducing parameter uncertainty. For example, Han et al. [41] used probabilistic modelling to explore how fluctuations in electricity prices, electrolyzer efficiency, and CO_2 availability affect the levelized cost of methanol. These models provide insight into the sensitivity of outcomes to key variables and help identify thresholds for financial viability [41]. However, despite their sophistication, they often retain a fundamental abstraction: the treatment of CO_2 as a uniform, clean input. Source variability—including impurity loads, temporal stability, and required purification—is rarely factored into stochastic parameters, limiting the realism of modelled outputs [40,41,45].

MCDA frameworks go further in integrating multiple, often non-commensurable criteria—such as emissions reduction, water usage, land footprint, and social acceptance—into structured decision processes [44,46]. For instance, Tock et al. [44] applied MCDA to optimize carbon utilization pathways across competing environmental and economic goals. The strength of MCDA lies in its adaptability to complex decision contexts, including multi-stakeholder settings or long-term planning. Yet, its flexibility also introduces subjectivity, as the selection and weighting of criteria are often expert-driven and context-dependent [47]. Moreover, MCDA applications in CO_2 utilization typically compare product pathways (e.g., methanol vs. methane vs. urea), rather than comparing the viability of different CO_2 sources for the same product [48]. This limits their applicability in source-specific feasibility analysis.

A deeper limitation of both Monte Carlo and MCDA approaches is their reliance on static or idealized inputs. Even when models incorporate policy incentives (e.g., carbon credits or hydrogen subsidies), these are frequently treated as fixed over the project lifetime, failing to reflect regulatory volatility or eligibility complexity [49,50]. Similarly, variables such as waste heat availability, electricity grid constraints, water access, and hydrogen logistics are either assumed to be constant or excluded—despite being pivotal for real-world integration [51–55]. This detachment from physical and regulatory constraints narrows the operational utility of these models, mirroring the limitations identified in TEA studies where location-specific variables—such as proximity to hydrogen supply, access to low-carbon electricity, and land or permitting constraints—are rarely embedded into the assessment framework [36,37]. These tools have advanced the analytical frontier by embracing uncertainty and multidimensionality, yet they remain constrained by the same core blind spot as LCA and TEA: the assumption of CO_2 interchangeability [16–18,40,41,45]. By abstracting away the chemical, logistical, and infrastructural heterogeneity of CO_2 sources, these models risk generating deployment strategies that are elegant in theory but infeasible in practice [51–55].

The current review addresses this oversight by re-centering feasibility analysis around the operational realities of CO_2 sources. Rather than expanding criteria alone, we argue for a framework that integrates source-specific constraints—including hydrogen delivery challenges, contaminant profiles, integration complexity and policy exposure,—into a comparative structure [51,53–55]. The five-axis viability framework introduced in the next section offers such an approach, drawing from the flexibility of MCDA while grounding its metrics in deployment-level granularity [43,44,46–48].

2.4. Summary of gaps and the need for a new framework

The preceding analysis reveals a consistent and consequential limitation in existing feasibility assessments of CO_2-to-methanol synthesis: while they offer detailed insights into process design, emissions reduction potential, and cost structures, they systematically overlook how both CO_2 and H_2 source characteristics—and their interactions with catalysts and infrastructure—shape deployment outcomes [16–18,36,37,40,41,43–48]. Whether through idealized purity assumptions in LCA, generic hydrogen pricing in TEA, or the absence of contaminants and site constraints in MCDA and Monte Carlo simulations, the upstream realities of CO_2 capture and integration are treated as background details rather than design-defining variables [50,51,53].

This oversight is especially problematic given the diversity of CO_2- and H_2 emitting industries now being considered for methanol production. A flue gas stream from a cement kiln is chemically and logistically distinct from CO_2 recovered from a biogas digester or a steel furnace, just as electrolytic hydrogen from renewables differs in intermittency and cost structure from hydrogen derived from natural gas reforming or industrial by-products [51,53]. These differences are not limited to composition—they affect contaminant removal costs, hydrogen coupling potential, infrastructure synergies, and policy eligibility [51,53,55]. Yet most existing frameworks treat CO_2 and H_2 as if it were interchangeable across contexts, leading to assessments that may be internally consistent but externally misleading.

To illustrate the extent of heterogeneity across industrial CO_2 sources that is often neglected in feasibility assessments, Table 1 summarizes key descriptive characteristics of representative emitters relevant to methanol synthesis. These include CO_2 concentration, contaminant profiles, co-stream reforming potential, hydrogen dependency, and capture complexity, based on reported industrial data and case studies. The parameters in Table 1 are presented for comparative and contextual purposes only and serve as input evidence for the viability assessment framework introduced in Section 3; no scoring or ranking is performed at this stage.

Moreover, the reviewed literature—though rich in coverage of catalysts, reactor configurations, and downstream integration—rarely offers comparative insight into how different CO_2 and H_2 sources constrain

Table 1
Comparative characteristics of major industrial CO_2 sources relevant to methanol synthesis. Key attributes include CO_2 concentration, contaminant profile, quantity available, presence of reformable co-streams, hydrogen co-feed dependency, and capture complexity. Qualitative descriptors (Low–Very High) indicate relative technical magnitude based on industrial benchmarks and reported process data and are used for descriptive comparison only. Data summarized from case studies and industrial reports.

Source	CO_2 Conc.	Key Contaminants	Major Gas-Phase Components	Typical CO_2 Volume (kt/y)	Reforming Potential	H_2 Requirement	Capture Complexity	Ref
Biogas	30–50%	H_2S, NH_3, siloxanes	CH_4 (50–70%)	~5–50	High (co-reforming)	Low	Moderate	[54]
Cement	20–35%	NO_x, SO_x, dust	CO_2, N_2	~100–1000	None	High	High	[52, 53]
Steel	20–30%	CO, tars, metals	CO, H_2, CH_4	~200–1500	Moderate (blending)	Medium	High	[54, 55]
WtE	5–15%	Dioxins, Hg, O_2	N_2, O_2 (non-reformable)	~50–300	Low	High	Very High	[51]

or enable methanol synthesis [5,14,19]. The tendency to isolate individual process elements (e.g. catalyst activity, reactor configuration, or energy intensity) without linking them to feedstock realities creates a persistent gap between theoretical modelling and industrial deployment. This disconnect is further widened by the limited incorporation of policy volatility and infrastructure readiness into feasibility evaluations, despite these being decisive factors in project risk and bankability [54, 55].To consolidate the critical insights from this literature review and clarify how existing frameworks fall short. Table 2 summarizes the scope, strengths, and key limitations of major assessment methodologies—LCA, TEA, MCDA, and stochastic modelling—as well as existing reviewed literature. Notably, none of these approaches adequately account for CO_2 and H_2 source variability, catalyst-contaminant interactions, or infrastructure-policy interfaces [51,53–55]. These gaps highlight the need for a more holistic, subsystem-integrated approach.

The five-axis viability model introduced in Section 3 addresses these deficiencies by providing a structured framework that links feedstock characteristics, catalyst robustness, integration complexity, and policy exposure to overall methanol synthesis viability. The remainder of this review introduces a structured, comparative framework built around five axes of viability: CUP, HVI CLF, ICS, and PRE. Collectively, these axes extend viability assessment beyond CO_2 sources to encompass hydrogen pathways, catalyst systems, and integration contexts. By re-centering feasibility analysis on the interaction between sources and subsystems rather than the process alone, this approach enables more grounded, context-responsive deployment strategies for CO_2-to-methanol technologies.

Table 2
Summary of limitations in existing assessment frameworks and alignment with the proposed five-axis viability model.

Framework	Typical Focus	Strengths	Key Limitations
Life Cycle Assessment (LCA)	Environmental impacts (GHG, energy use)	Standardized, widely adopted	Ignores source-specific impurity loads, pre-treatment energy, and boundary inconsistencies
Techno-Economic Assessment (TEA)	CAPEX, OPEX, cost curves, payback	Quantifies economic feasibility	Assumes ideal inputs, overlooks logistics of CO_2/H_2 integration
Monte Carlo Sensitivity Analysis	Parameter uncertainty (e.g., electricity cost, efficiency)	Captures stochastic behaviour	Still assumes standardized CO_2 inputs; no contaminant modelling
Multi-Criteria Decision Analysis (MCDA)	Multi-dimensional trade-offs	Flexible, adaptable	Subjective weighting; limited in technical realism

3. Methodology: toward a source-responsive feasibility framework (The five-axis approach)

3.1. Conceptual basis and scope of the framework

While recent approaches have improved on traditional LCA and TEA by including spatial, contaminant, or policy elements [37,56] they do not offer a holistic methodology for comparing the multidimensional feasibility of methanol synthesis across CO_2, H_2, and catalytic subsystems. Existing assessments typically isolate process elements (carbon capture, hydrogen production, or catalysis) without considering how constraints in one domain propagate through the others.

To address this gap, the present review develops a source-responsive feasibility framework that integrates technical, logistical, and policy factors into a coherent evaluative structure. The framework is organized around five interdependent axes of viability that collectively define the feasibility space for CO_2-to-methanol synthesis: the CUP, HVI, CLF, ICS, and PRE. Originally conceived to assess CO_2, point sources, these axes are generalized here to encompass subsystem interactions across the entire methanol synthesis chain. These five axes constitute the formal basis for the comparative assessment developed in this review. By treating feasibility as an emergent property of coupled feedstocks and infrastructures rather than of isolated processes, this framework extends beyond conventional TEA or LCA boundaries. Each axis serves as both a diagnostic metric and a decision lever, allowing systematic comparison across industrial contexts. Together, they enable a structured, semi-quantitative evaluation of how feedstock quality, catalyst tolerance, integration readiness, and policy stability converge to determine the real-world viability of CO_2, -to-methanol pathways. The subsequent subsections define each axis, describe the semi-quantitative scoring criteria and data sources (Sections 3.2–3.3), and allocate scores that are reproducible and auditable for each of the point sources considered; the details have been summarized in Appendix A.

3.2. Operationalizing the five-axis viability framework

3.2.1. Deconstructing the viability axes

A rigorous assessment of CO_2, -to-methanol feasibility requires more than acknowledging that different point sources possess distinct chemical and logistical characteristics; it demands a structured means of translating these variations into comparable viability constraints. Building on the conceptual framework defined in Section 3.1, this section operationalizes the five-axis framework to enable systematic, semi-quantitative comparison across CO_2 sources, hydrogen supply pathways, and catalytic subsystems.

The viability framework is structured around five interdependent axes: CUP, HVI, CLF, ICS, and PRE. Together, these axes provide a consistent lens for evaluating thermodynamic, infrastructural, and regulatory dimensions of feasibility. Each axis has a primary domain of application yet extends conceptually across subsystems –CO_2 sources, hydrogen supply, and catalytic configuration-reflecting the

interdependence among feedstock quality, hydrogen logistics, catalyst robustness, and integration context.

(i) CUP captures the energy and process burden required to condition raw gases into synthesis-grade CO_2, encompassing impurity removal, compression, and pressure alignment. (Note that this dimension can also be applied to hydrogen giving rise to the *Hydrogen Usability Potential (HUP)*, representing purification or pressurization energy prior to integration. For catalysts, CUP indirectly reflects tolerance to upstream gas variability.
(ii) HVI measures how a system's viability depends on reliable, affordable and low-carbon hydrogen supply. It considers both supply-side risks—such as intermittency of renewable electricity, transport logistics, and grid carbon intensity—and downstream processing requirements driven by low CO_2 purity. Applied to catalysts, HVI accounts for tolerance to fluctuating H_2/CO_2 ratios or hydrogen impurity sensitivity.
(iii) CLF quantifies the combined impact of chemical impurities—such as sulfur, halogens, metals, and siloxanes—on process performance. In CO_2 streams, CLF reflects the complexity of pretreatment; in hydrogen subsystems, it covers contamination from recycled or waste-derived hydrogen (e.g., O_2, CO, or moisture); and in catalysts, it represents the propensity for poisoning or deactivation under real feed conditions.
(iv) ICS evaluates the infrastructural and spatial challenges associated with coupling CO_2 capture, hydrogen production, and methanol synthesis. It captures co-location potential, thermal or electrical synergies, and the degree of retrofit feasibility. At subsystem level, ICS applies to both hydrogen (integration with renewable generation and water access) and catalysts (process modularity, reactor design compatibility, and thermal coupling).
(v) Finally, the PRE measures dependence on volatile or geographically variable policy mechanisms—carbon credits, renewable fuel classifications, or hydrogen subsidies—that can decisively affect project bankability. For CO_2 sources, it indicates eligibility within carbon capture and utilization (CCU) frameworks; for hydrogen, it captures the sensitivity to production taxonomy (e.g., green, blue, or pink); and for catalysts, it links to regulatory exposure tied to critical metal sourcing and recycling mandates.

By translating these five axes into a unified comparative framework, the model provides a structured and transferable means to evaluate diverse CO_2 sources and related subsystems on equal methodological footing. The resulting multidimensional matrix enables both source-specific feasibility analysis and cross-domain generalization, facilitating comparative insight into how upstream heterogeneity cascades through downstream performance. Detailed scoring logic, numerical threshold and reproducibility criteria for each axis are defined in sections 3.2.2-3.3 and fully specified in Appendix A.

3.2.2. Scoring methodology and criteria

To operationalize this five axis framework, a semi-quantitative scoring system was developed in which each axis is evaluated on a uniform ordinal scale from ranging from 1 (least favourable) to 5 (most favourable). This approach enables consistent comparison across different CO_2 sources, hydrogen supply pathways, and catalytic systems while retaining traceability to empirical and model-derived data. Each axis score is derived from three complementary information streams.

(i) empirical data from literature (e.g., energy penalties, CO_2, concentration, contaminant levels, hydrogen transport distances),
(ii) process modelling and engineering insights (e.g., reforming compatibility, catalyst stability trends), and
(iii) contextual and infrastructural assessments reflecting integration feasibility, retrofit complexity and policy stability

Collectively, these inputs enable semi-quantitative representation of multidimensional viability factors. Each axis follows a defined scoring rationale, ensuring consistency across use cases and subsystems. Scores are anchored in reported numerical ranges and industrial benchmarks but are not intended to represent absolute performance metrics. Rather, they express relative feasibility under comparable assumptions, enabling ranking and cross-source comparison. Representative threshold ranges and quantitative anchors used to assign scores are summarized in Section 3.3 and detailed exhaustively in Appendix A, where treatment of missing or uncertain data is also specified. Each axis contributes an equal baseline weighting (20%) to the aggregate viability score. This assumption is supported by sensitivity analysis (Appendix A), which shows less than 10% variation in relative rankings when any single axis weighting is doubled, confirming limited dominance by any individual dimension.

3.3. Scoring logic and thresholds

This section defines the procedural logic used to assign numerical scores to the five viability axes introduced in Section 3.2. The goal of this step is not absolute quantification of feasibility metrics, but to ensure consistent, evidence-based, and reproducible comparison across heterogeneous CO_2 sources, hydrogen supply routes, and catalytic subsystems. Each axis was evaluated using predefined numerical or categorical thresholds derived from reported process data, industrial benchmarks, and peer-reviewed techno-economic assessments. Qualitative descriptors introduced in Section 3.2 were translated into quantitative score ranges on a five-point scale (1 = least favourable, 5 = most favourable) using literature-informed boundary values. All thresholds were defined a priori and applied uniformly across all cases.

Thresholds were derived primarily from peer-reviewed techno-economic assessments, life cycle analyses, and industrial datasets relevant to CO_2 capture, purification technologies, hydrogen production and transportation systems, and industrial methanol synthesis performance. For instance, CUP was benchmarked for post-combustion amine scrubbing, pressure swing adsorption, and membrane separation systems [51,53]. Tolerable contaminant limits and catalyst deactivation thresholds were informed by long-term industrial methanol synthesis trials and laboratory poisoning studies [54,55]. Hydrogen-related parameters were adapted from spatial coupling and infrastructure assessments of green hydrogen hubs [57,58]. Integration complexity metrics reflected site-level analyses of grid integration, water access, and process co-location feasibility [59,60]. Finally, the policy dimension was parameterized through comparative reviews of carbon capture and utilization (CCU) and hydrogen-support frameworks, including the EU ETS Phase IV, the U.S. Inflation Reduction Act (45Q/45V), and related national renewable fuel standards [50–52]. When multiple literature sources reported differing values for a given parameter, representative or median values were used. In cases of residual uncertainty or incomplete data, conservative scoring was applied to avoid overestimating viability. No axis score was assigned without traceable justification to published data or clearly stated assumptions. The resulting quantitative thresholds used to assign axis-specified scores across CO_2, hydrogen and catalyst subsystems are, summarized in Table 3. Expanded threshold ranges, source-specific data, treatment of missing information, and uncertainty considerations are provided in Appendix A.

4. Comparative source analysis using the five-axis framework

4.1. Source-specific viability assessment

This section applies the five-axis framework developed in Section 3 to four representative CO_2 point sources—biogas, steelworks, cement kilns, and waste-to-energy (WtE) facilities—to evaluate how source-specific characteristics shape methanol synthesis feasibility. Rather than listing chemical compositions alone, the discussion interprets how

Table 3
Primary thresholds ranges used to anchor the five-axis viability scoring across CO_2, H_2, and catalyst subsystems. These ranges provide indicative boundaries used to inform the ordinal 1–5 scoring rubric applied in Table 4 and detailed fully in Appendix A.

Axis	Primary Parameter	Favourable (score 4-5)	Transitional (scores 3)	Constraint (scores 1-2)	Reference Basis
CUP	CO_2 capture & purification energy (GJ t^{-1} CO_2)	<2	2–4	>4	[51–53]
HVI	Hydrogen carbon intensity/supply distance	<0.5 kg CO_2e kg^{-1} H_2 or < 10 km	0.5–2 kg CO_2e kg^{-1} H_2 or 10–50 km	>2 kg CO_2e kg^{-1} H_2 or > 50 km	[57,58,61]
CLF	Total contaminant burden (ppm)	<10	10–100	>100	[57,58,61],
ICS	Distance to shared infrastructure/retrofit feasibility	Co-located (<5 km)	Partial (5–20 km)	Stand-alone (>20 km)	[54,55]
PRE	Duration & clarity of policy support	>10 years stable	5–10 year or regionally variable	<5/unclear	[54,55]

Note: Full 1–5 scoring criteria, treatment of uncertainty, and axis-specific justification are provided in Appendix A, which constitutes the authoritative scoring rubric.

each axis (CUP, HVI, CLF, ICS, and PRE) collectively defines a distinct viability profile for each source. Comparative results are summarized in Table 4 and interpreted using the unified 1-5 ordinal scoring system defined in Section 3.3 and supported by literature-derived process data and case studies [51–53].

Biogas represents a renewable yet compositionally variable CO_2 source, typically containing 30–50 % CO_2 and up to 75 % CH_4 [62–64]. Its moderate concentration yields a favourable CUP (≈4) since capture energy remains <2 GJ t^{-1} CO_2. Hydrogen vulnerability is context-dependent: co-reforming of CH_4 lowers HVI (≈3) by generating syngas internally, but on-site electrolysis remains capital-intensive ($1000–1700 kW^{-1}) and water-demanding (conductivity <1 μS cm^{-1}) [65–68]. However, the CLF is limited by impurities— H_2S (up to 2 %), NH_3 (~100 ppm), and siloxanes (~0.02 %)—necessitating multi-stage clean-up and adsorbent replacement (CLF = 2) [29,69–71]. Where renewable power is intermittent, storage or oversizing adds ≈15–20 % energy losses [72–76]. Integration complexity is moderate (ICS ≈ 3): biogas plants are decentralized but can co-locate with renewable micro-grids or biogenic feed hubs. Policy risk varies with carbon-credit schemes; EU recognition of biogenic origin grants favourable accounting (PRE ≈ 3). European biogas upgrading facilities already demonstrate partial integration of CO_2 recovery with downstream synthesis routes. For example, biomethane upgrading plants in Denmark and the Netherlands (e.g., Nature Energy's installations) generate high-purity CO_2 streams that have been proposed for methanol synthesis with moderate clean-up needs. These facilities illustrate CUP and CLF performance consistent with the present framework, with CO_2 concentrations of 35–45% enabling relatively low capture energy requirements and limited sulfur/halogen content after standard biogas clean up. Overall, biogas achieves balanced feasibility but remains limited by scale and integration infrastructure.

Table 4
Source-specific viability scores for methanol synthesis using five-axis framework: CO2 Usability Potential (CUP), Hydrogen Vulnerability Index (HVI), Contaminant Load Factor (CLF), Integration Complexity Score (ICS), and Policy Risk Exposure (PRE). Scores are assigned on a 1-5 ordinal scale, where higher values indicate more favourable feasibility conditions. Total scores represent overall relative viability (maximum = 25). These data are visualized in the radar plot shown in Fig. 1.

Criteria	Biogas	Steel Off-Gas	Cement Kilns	Waste-to-Energy (WtE)
CUP – CO_2 Usability Potential	4	4	2	1
HVI – Hydrogen Vulnerability Index	3	3	2	2
CLF –Contaminant Load Factor (Tolerance)	2	3	2	1
ICS – Integration Complexity Score	3	4	1	1
PRE – Policy Risk Exposure	3	4	2	1
Total Viability Score (out of 25)	**15**	**18**	**9**	**6**

Steelworks gases, especially blast furnace gas (BFG) and coke oven gas (COG), contain 20–30% CO_2, 20–30% CO, and significant H_2, yielding favourable CO_2 usability (CUP = 4) and low hydrogen vulnerability (HVI = 3) [54,55]. Their near-syngas composition supports partial *in situ* methanol synthesis, minimizing additional H_2 input. Importantly, reforming systems associated with such streams can be optimized to achieve target syngas ratios while minimizing carbon loss, especially when integrated with renewable hydrogen and oxygen loops. Recent studies show that such system-level optimization can improve methanol yield and carbon efficiency while reducing the overall energy and environmental penalty [77]. However, contaminants such as tars, hydrocarbons, and heavy metals necessitate purification stages to protect Cu/ZnO-based catalysts (CLF = 3) [55]. Integration Complexity (ICS) scores highest (4) among all sources: steel plants typically possess waste-heat recovery, gas-handling systems, and available land for modular retrofits [78]. The Policy Risk Exposure (PRE) is moderate (4)—many steel decarbonization strategies align with EU and national green-steel programs. Despite feed variability, steel off-gases emerge as the most technically viable CO_2 source for methanol synthesis under current industrial conditions. The Carbon2Chem demonstration operated by Thyssenkrupp in Germany provides a direct industrial example of integrating steel off-gases with methanol synthesis. Here, blast furnace gas and coke oven gas are reformed and catalytically converted into methanol precursors, supported by on-site electrolytic hydrogen. This system exemplifies the relatively favourable CUP and ICS scores assigned in the present study while illustrating moderate CLF burdens arising from sulfur, tars, and metal contaminants intrinsic to steel off-gases.

Cement flue gases offer large-volume but low-quality CO_2 streams (20–35 %) laden with particulates, SO_x, NO_X, and alkali metals [52,53,79]. The high impurity and dilution lowers the CUP to 2 (>4 GJ t^{-1} CO_2) and necessitate intensive pre-treatment [80]. Complete reliance on imported hydrogen yields the lowest HVI (2): truck-delivered H_2 suffers 10–15 % compression losses for CGH_2 and 30–40 % liquefaction losses for LH_2 [72–76]. With no reformable co-stream and limited renewable electricity access, on-site electrolysis is economically impractical. CLF scores (≈2) reflect catalyst deactivation by alkali aerosols and dust, partially mitigated by In_2O_3-based catalysts [81,82]. ICS remains low (2) due to isolated locations and restricted water supply. Policy risk (PRE ≈ 2) is region-specific: EU ETS and CCS integration schemes enhance prospects, whereas North American plants lag under weaker carbon pricing. Cement kilns therefore represent high-volume but technically constrained sources needing policy-driven hydrogen infrastructure to improve viability [83,84]. Multiple pilot projects have evaluated cement-derived CO_2 for methanol synthesis, most notably the Shandong CCU pilot in China, where kiln CO_2 is captured, purified, and hydrogenated to methanol and dimethyl ether. The system demonstrates the challenges reflected in this framework: high-temperature flue gas enables moderate CUP performance, but low CO_2 concentration and particulate/alkali contaminants elevate CLF and ICS burdens. This pilot provides a practical demonstration of the viability limits of cement

streams for decentralized methanol production.

WtE facilities emit low-CO_2, high-O_2 flue gases (5–15% CO_2, 5–10% O_2) rich in dioxins, furans, and toxic metals (Hg, Pb, Cd) [85,86]. These properties yield the lowest CUP (1) and CLF (1) scores, as energy required for gas purification exceeds potential methanol energy yield [86]. Hydrogen must be fully imported (HVI = 2), and delivery losses (25–35 %) via LH_2 or CGH_2 logistics further erode feasibility [73,87,88]. ICS is minimal (≈1) due to urban siting and limited space for hydrogen storage. Although PRE may improve under circular economy and waste valorization policies, WtE currently ranks as the least viable methanol source (total score ≤6/25). Nonetheless, emerging pathways, such as non-thermal plasma pre-treatment and hybrid carbon mineralization, offer long-term potential [52,89]. Conceptual engineering analyses for the Amager Bakke WtE facility (Copenhagen) have examined integration of flue-gas-derived CO_2 into methanol synthesis. These studies highlight the unfavourable CUP, CLF, and PRE characteristics captured in the present scoring: low CO_2 concentration (~12–14%), high impurity burden (including NO_x, SO_x, and metals), and multi-stage flue-gas clean-up requirements. The assessments align with the low viability scores assigned to WtE streams in this framework.

Fig. 1visualizes these data as radar plots, highlighting how steelworks achieve the most balanced feasibility envelope, while WtE falls well outside the viable domain under current conditions. The five-axis comparison confirms that no single variable determines feasibility—rather, it is the interdependence among thermodynamic, contaminant, and policy constraints that defines real deployment limits.

4.2. Contextual overrides and regional realities

While the five-axis framework provides normalized feasibility scores, real-world viability is often reshaped by contextual factors including geography, water availability, infrastructure, and policy asymmetries [52,53]. Water scarcity, for example, significantly degrades the hydrogen viability of biogas and cement systems in arid regions, where electrolysis competes with agricultural or municipal demands [57,58]. Conversely, coastal industrial clusters—such as Northern Europe's "Hydrogen Backbone" or Japan's port-based CCS hubs—enhance steel plant viability through ammonia-based hydrogen imports and grid connectivity [90]. Policy asymmetries also reshape comparative outcomes: European steel facilities benefit from "green steel" mandates and CBAM protections, while U.S. biogas and WtE initiatives depend heavily on the Inflation Reduction Act's 45Q/45V credits [18,90–92].

4.3. The decision implementation pathway

To operationalize the framework for policy and engineering use, a sequential decision pathway was developed to screen point sources based on threshold viability criteria derived from the unified 1-5 scoring system defined in Section 3 and Appendix A [51,53]. Each axis functions as a structured gate applied directly to the values reported in Table 4. The first gate applies to the CUP: point sources with CUP scores of 2 or less are constrained by high capture and conditioning penalties and are not prioritized for near-term decentralized development. Under the scoring in Table 4, this threshold affects cement (CUP = 2) and waste-to-energy (WtE) streams (CUP = 1), while biogas and steel off-gases remain above the threshold. Next HVI is considered and point sources with a score of 2 or less are classified as hydrogen-constrained and require verified low-carbon hydrogen supply prior to deployment rather than being automatically excluded. In Table 4, cement (HVI = 2) and WtE (HVI = 2) fall into this constrained category, whereas steel and biogas (HVI = 3) remain conditionally viable. [93,94]. Contaminant Load Factor (CLF): sources with a score ≤ 2are flagged due to unmanageable purification costs or catalyst instability. Rather than full exclusion, these are categorized as technically viable only with validated pre-treatment safeguards. Based on Table 4, biogas (CLF = 2) and cement (CLF = 2) require multistage clean-up, while WtE (CLF = 1) represents the most severe contamination burden. The final gate evaluates Integration Complexity (ICS): sources scoring 3 or more qualify for on-site or co-located methanol synthesis, while those ≤2 are better suited to centralized processing or hub-based integration via CO_2 transport [59,95]. Under this criterion, steel off-gas (ICS = 4) and biogas (ICS = 3) are compatible with on-site or semi-distributed deployment, while cement (ICS = 1) and WtE (ICS = 1) are more appropriately directed toward centralized utilization pathways. Policy Risk Exposure (PRE) functions as a contextual prioritization axis rather than a strict exclusion gate. It informs prioritization and deployment timing but does not independently exclude sources from consideration.

Overall, steel off-gas remains the only source that satisfies all gate

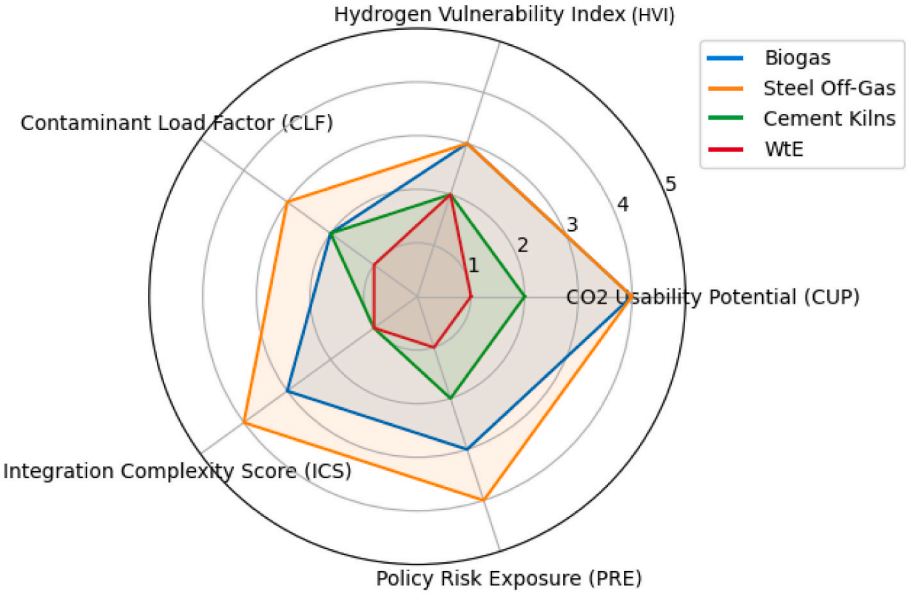

Fig. 1. Comparative radar chart illustrating source-specific performance across the five viability axes: CO_2 Usability Potential (CUP), Hydrogen Vulnerability Index (HVI), Contaminant Load Factor (CLF), Integration Complexity Score (ICS), and Policy Risk Exposure (PRE). Higher scores indicate more favourable conditions for methanol synthesis viability. Data derived from scoring criteria detailed in Section 3.3 and Appendix A.

thresholds without conditional requirements, aligning with industrial symbiosis models already piloted in Europe and Asia [54,55,89]. Biogas remains viable but contingent on contaminant (e.g. H_2S/siloxane) removal and hydrogen integration [69,70]. Cement and WtE streams are not excluded outright but are routed toward centralized or future deployment scenarios under current technological and infrastructure constraints. The structured decision sequence is illustrated in Fig. 2, where each axis functions as a sequential screening or routing mechanism linked directly to the master scoring dataset in Table 4.

4.4. Non-negotiable innovation frontiers

Bridging the viability gaps identified through the five-axis framework requires targeted innovation along four interdependent research frontiers: (i) hybrid capture–conversion systems to increase the CUP; (ii) impurity-resilient catalysts to mitigate CLF constraints; and (iii) flexible hydrogen and integration strategies to strengthen the HVI and Integration ICS. These frontiers represent the immediate pathways for transforming theoretical feasibility into deployable technology.

(i) Hybrid capture–conversion architectures.

Sequential CO_2 capture and methanol synthesis introduces cumulative energy penalties exceeding 4 GJ t^{-1} CO_2. Hybrid configurations that merge absorption and conversion steps can reduce this burden by 30–40% [57,58]. Functionalized amine solvents doped with transition metals (e.g., Cu-doped MEA blends) enable in-situ CO_2 hydrogenation during desorption, minimizing intermediate conditioning [96,97]. Although current Faradaic efficiencies remain below 5% due to carbonate crossover [61,95], progress in membrane conductivity and electrolyte management could render such systems viable for decentralized CO_2 utilization.

(ii) Hydrogen–catalyst co-design and impurity tolerance.

Catalyst performance under realistic gas compositions remains the most critical barrier to closing the CLF gap. Sulfur-resistant Pd–Zn alloys maintain activity in hydrogen streams containing up to 5 ppm H_2S, demonstrating compatibility with steel-mill off-gases [59]. Likewise, In-based and Cu–In intermetallic catalysts exhibit CO tolerance under CO-rich reformate conditions typical of steel and dry-reforming environments, suppressing competing reactions and methanation [60]. For halogen-containing waste-derived hydrogen, Ni–Ga and Cu–In alloys resist chlorine poisoning and maintain long-term selectivity [90]. Co-engineering catalyst formulations alongside hydrogen purification systems is therefore essential for robust deployment across variable feedstocks.

(iii) Flexible hydrogen infrastructure and integration synergies.

Achieving high HVI and ICS scores requires strong spatial and temporal coupling between CO_2 emitters and renewable hydrogen production assets. Modern PEM and SOEC electrolyzers now offer rapid ramping capabilities, enabling integration with variable renewable electricity when supported by short-term energy storage. Modular electrolyzer arrays, ammonia-based hydrogen carriers, and dynamic power-to-methanol configurations further increase operational resilience under intermittency conditions [98]. Recent integrated assessments demonstrate that power–hydrogen–methanol systems can maintain stable synthesis performance even with fluctuating renewable inputs [99]. Coupled process modelling and geographic information system (GIS) mapping should therefore be prioritized to evaluate co-location potential and optimize infrastructure layout, reducing the extent to which hydrogen logistics dictate CO_2 source viability.

While co-location of CO_2 emitters and methanol plants can reduce compression and transport costs, it is not a strict requirement for viable deployment. CO_2 can be transported as a compressed gas (typically 80–150 bar), as refrigerated liquid CO_2 (−20 to −30 °C), or via pipeline networks where available. Transport costs range from 1 to 4 € t^{-1} km^{-1} for pipelines, 0.1–0.3 € t^{-1} km^{-1} for ship transport at scale, and 10–25 € t^{-1} for trucked liquid CO_2 over regional distances, depending on pressure, flow rate, and terrain. As a result, siting the methanol plant closer to low-cost renewable hydrogen hubs may be more advantageous than building directly adjacent to the CO_2 source—an especially relevant option for cement kilns, small emitters, and isolated industrial facilities. ICS scoring has therefore been updated to reflect not only emitter-side integration but also the feasibility of CO_2 transport to hydrogen-rich industrial clusters.

Taken together, these innovation vectors define a non-negotiable research agenda for next-generation methanol synthesis: one that simultaneously reduces capture penalties, hardens catalysts against contamination, and decouples hydrogen dependence from geographic and policy uncertainty. Continued alignment between process intensification, catalysis science, and systems integration will be pivotal for

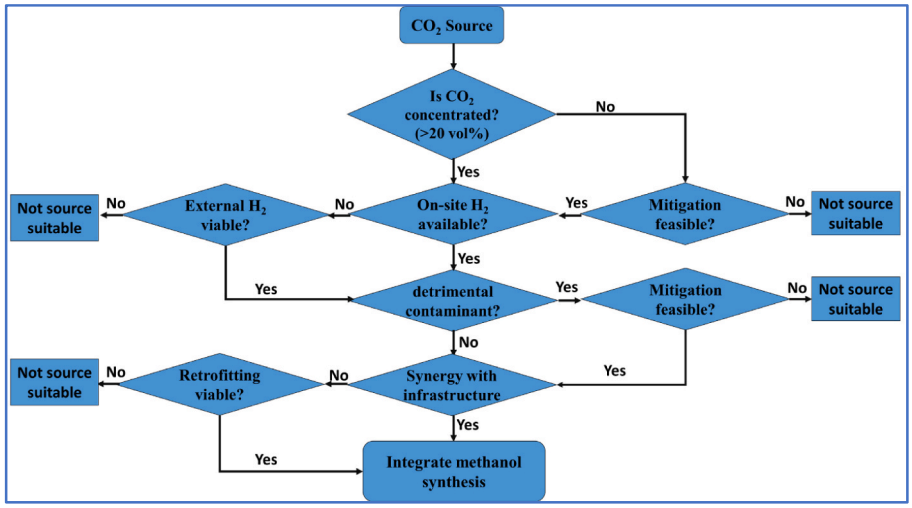

Fig. 2. Integration decision flowchart for evaluating the feasibility of methanol synthesis from industrial CO_2 sources. The diagram outlines a sequential viability screening process based on key criteria: CO_2 concentration, hydrogen availability (on-site or external), contaminant burden, and infrastructure compatibility. Paths that fail at each stage may still proceed if mitigation or retrofitting is feasible. The framework reflects the five viability axes—CUP, HVI, CLF, ICS, and PRE—and translates them into an actionable decision-tree assessment. This decision logic complements the scoring synthesis presented in Sections 3.

advancing CO_2-to-methanol technologies from conceptual frameworks to industrial implementation.

5. Conclusions and outlook

This review has developed and operationalized a five-axis viability framework comprising the CUP, HVI, CLF, ICS, and PRE to assess the real-world feasibility of CO_2-to-methanol synthesis across industrial point sources. By integrating thermodynamic, logistical, and policy dimensions, the framework provides a structured, comparative basis for evaluating deployment readiness beyond conventional techno-economic or lifecycle boundaries.

Application of the framework to four representative CO_2 sources (i.e. biogas, cement kilns, steelworks, and waste-to-energy (WtE)) revealed pronounced contrasts in viability profiles. Steelworks off-gases emerged as the most technically and infrastructurally favourable, supported by intrinsic CO/H_2 content and established utilities (total score ≈ 18/25). Biogas presented moderate feasibility (≈15/25), balancing renewable origin and co-reforming potential against persistent contaminant burdens and integration challenges. Cement kiln exhausts exhibited high capture penalties and total hydrogen dependence, producing low aggregate scores (≈9/25). WtE emissions are ranked least viable (≈6/25), with low CO_2 concentration and complex pollutant matrices rendering current methanol synthesis impractical. These findings affirm that source-specific characteristics, not generalized process metrics, govern the feasibility landscape of carbon utilization pathways.

The five-axis framework advances current feasibility modelling by embedding multi-dimensional comparability into CO_2-to-methanol analysis. Unlike deterministic LCA or TEA approaches, it explicitly captures non-linear trade-offs among energy penalties, contamination risks, infrastructure constraints, and policy stability. Its cross-domain adaptability, extending CUP to hydrogen (HUP) and CLF to catalyst performance, enables unified evaluation of feedstock, hydrogen, and reactor subsystems on a consistent methodological footing. Beyond methanol, the framework offers a transferable decision platform for assessing other CO_2 utilization routes such as formic acid, DME, or synthetic hydrocarbons.

The sequential gatekeeping logic introduced in Section 4.3 offers a practical decision-support pathway for technology developers and policymakers. Projects with CLF >2, HVI >3, and ICS >3 qualify for near-term methanol synthesis deployment, while lower scores suggest redirection toward mineralization, fuel blending, or storage routes. From a regulatory perspective, the framework highlights the need for aligned carbon policy instruments that reward actual deployment feasibility rather than nominal emission reduction potential. In particular, policy stability (PRE) and access to renewable hydrogen infrastructure (HVI) emerge as decisive enablers of industrial-scale implementation.

CRediT authorship contribution statement

Lebohang Macheli: Writing - original draft, review & editing, Formal Analysis and Visualization. Bahizire Martin Mukeru: Writing - review & editing. Zama Duma: Writing – review & editing, Bilal Patel: Writing – review & editing, Linda L. Jewell: Conceptualization, Writing – review & editing, funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Five-Axis Viability Scoring Rubric and Auditability Framework

A.1. Purpose and Scope

This appendix provides the complete, reproducible scoring rubric used to operationalize the five-axis viability framework introduced in Section 3. Each axis—CO_2 Usability Potential (CUP), Hydrogen Vulnerability Index (HVI), Contaminant Load Factor (CLF), Integration Complexity Score (ICS), and Policy Risk Exposure (PRE)—is evaluated on a uniform ordinal scale from 1 to 5, where higher values indicate more favourable feasibility conditions.

The rubric is designed to.

1. Ensure internal consistency across all axes;
2. Enable independent reproduction of scores by external readers; and
3. Provide a transparent audit trail linking assigned scores to physical, infrastructural, or policy attributes reported in the literature.

Scores are comparative rather than absolute, reflecting relative feasibility under harmonized assumptions rather than site-specific project design.

A.2. General Scoring Principles

- Score = 5 represents conditions that are intrinsically favourable and impose minimal penalty or risk.
- Score = 1 represents conditions that are fundamentally incompatible with practical CO_2-to-methanol deployment under current technology.
- Intermediate scores (2–4) capture gradations in feasibility.
- Where quantitative data are unavailable, conservative mid-range scores (2–3) are assigned, and uncertainty is explicitly noted.
- All scores are supported by published benchmarks, industrial case studies, or well-established techno-economic analyses.
- Each axis is scored independently. Equal weighting (20% per axis) is applied in aggregate scoring, as justified by sensitivity analysis (Appendix A.6).

A.3. Axis-Specific Scoring Rubrics

A.3.1. CO_2 Usability Potential (CUP)

Definition: Energy and process burden required to condition raw CO_2 into synthesis-grade feedstock, including capture, purification, and compression.

Score	Criteria (CO_2 capture + conditioning energy)
5	<1.5 GJ t^{-1} CO_2; high-purity or pressurized streams (e.g., biogas upgrading, oxy-fuel)
4	1.5–2.0 GJ t^{-1} CO_2; moderate purification required
3	2.0–3.0 GJ t^{-1} CO_2; standard post-combustion capture
2	3.0–4.0 GJ t^{-1} CO_2; dilute flue gas, high inert content
1	>4.0 GJ t^{-1} CO_2; highly dilute or oxygen-rich streams

Audit indicators: CO_2 concentration, capture technology type, reported energy penalties.

A.3.2. Hydrogen Vulnerability Index (HVI)

Definition: Sensitivity of methanol synthesis viability to hydrogen availability, cost, carbon intensity, and logistical reliability.

Score	Criteria
5	On-site renewable H_2 (<0.5 kg CO_2e kg^{-1} H_2), stable supply
4	Nearby renewable hub (<10 km) or reformable co-streams
3	Moderate transport distance (10–50 km) or mixed grid supply
2	Trucked compressed or liquefied H_2; high energy penalties
1	Imported H_2 with high carbon intensity (>2 kg CO_2e kg^{-1} H_2)

Audit indicators: H_2 source, transport mode, carbon intensity, intermittency exposure.

A.3.3. Contaminant Load Factor (CLF)

Definition: Aggregate impact of impurities on purification complexity and catalyst lifetime.

Score	Criteria (total contaminants)
5	<5 ppm; negligible catalyst impact
4	5–10 ppm; single-stage clean-up
3	10–50 ppm; moderate pre-treatment
2	50–100 ppm; multistage clean-up
1	>100 ppm; rapid catalyst deactivation

Audit indicators: Presence of S, halogens, metals, siloxanes; reported deactivation rates.

A.3.4. Integration Complexity Score (ICS)

Definition: Infrastructure, spatial, and retrofit complexity associated with integrating capture, hydrogen, and synthesis units.

Score	Criteria
5	Fully co-located; shared utilities and waste heat
4	Minor retrofit; <5 km integration distance
3	Partial integration; 5–20 km separation
2	Major retrofit or new infrastructure required
1	Severe spatial or regulatory constraints

Audit indicators: Land availability, distance to utilities, retrofit feasibility.

A.3.5. Policy Risk Exposure (PRE)

Definition: Exposure of project viability to unstable, short-term, or ambiguous policy support mechanisms. Unlike CUP, HVI, CLF, and ICS, PRE is applied as a contextual weighting axis and is not used as an exclusionary gate in the sequential decision pathway.

Score	Criteria
5	>10 years stable eligibility (e.g., EU ETS IV, IRA 45V)
4	5–10 years moderately stable incentives
3	Transitional or regionally variable support
2	Short-term or uncertain eligibility
1	Policy support highly volatile or contested

Audit indicators: CCU eligibility, hydrogen taxonomy, carbon credit permanence.

A.4. Treatment of Missing or Uncertain Data

Where quantitative data are unavailable.

- Scores default to 3 (moderate feasibility) unless evidence suggests otherwise.
- Conservative downward adjustment (−1) is applied when uncertainty poses operational risk.
- All such cases are explicitly noted in score justification tables.

A.5. Score Auditability and Traceability

For each CO_2 source evaluated in the Results section.

- A per-axis justification is provided
- Linked directly to literature references or industrial benchmarks,
- Allowing independent recalculation by readers using this appendix.

A.6. Sensitivity and Weighting Robustness

Equal weighting of axes (20% each) was tested by doubling individual axis weights. Relative source rankings changed by <10%, confirming that no single axis dominates the framework and supporting the robustness of the equal-weight assumption.

Data availability

No data was used for the research described in the article.

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