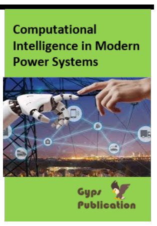
Computational Intelligence in Modern Power Systems, 1(1):1–10, 2026. DOI: 10.58613/cimps111

Computational Intelligence in Modern Power Systems

Journal homepage: https://gpub.org/journal-details.php?journal-id=49



Review Article

CO_2 Capture, Utilization, and Power-to-X Technologies for Sustainable Fuels and Energy Systems: A Review

Enoch Nii-Okai [1], **Bright Peter Saah** [2], **Adeniyi Adebayo** [3], **Gbangbala Usman Alao** [4], **Adedamola O. Oladunni** [5], **Anuligwe Chigozie Felix** [6] **and Benjamin Osaze Enobakhare** [7*]

[1] *Department of Geological and Mining Engineering and Sciences Michigan Technological University.*
[2] *Department of Civil and Environmental Engineering, Lehigh University, Bethlehem, PA, USA.*
[3] *Project and Construction department ATCO Electric, Edmonton, Alberta, Canada.*
[4] *Department of Renewable Energy Engineering, University of Aberdeen, Scotland.*
[5] *Substation Engineering, ComEd, IL, USA.*
[6] *Chemical Engineering Department Federal University of Technology Owerri, Imo state.*
[7] *Field Service Engineering Department, Service Support Engineer, Peterbilt Motors (PACCAR Inc), Denton, Texas, USA.*
[*] *Corresponding author: enobakharebenjamin@gmail.com*

Article Info

Keywords: *CO_2 capture and utilization, Power-to-X, synthetic fuels, system-level assessment, net-zero energy systems.*

Received: *30.11.2025;*
Accepted: *03.01.2026;*
Published: *11.01.2026*

Abstract

Carbon dioxide capture and utilization (CCU) and Power-to-X (PtX) technologies are increasingly viewed as key enablers of net-zero energy systems, particularly for decarbonizing sectors where direct electrification remains challenging. While a rapidly expanding literature has examined individual CCU and PtX processes, existing reviews largely adopt technology-centric perspectives with inconsistent system boundaries and assumptions, limiting comparability and obscuring system-level climate relevance. This review addresses this gap by providing an integrated, system-level synthesis of CO_2 capture, utilization, and Power-to-X pathways for sustainable fuels and energy systems. Building on a harmonized analytical framework, the review evaluates major capture routes, utilization pathways, and synthetic fuel options under consistent assumptions, with particular emphasis on energy demand, net CO_2 reduction, and sensitivity to electricity carbon intensity. The analysis demonstrates that overall performance is governed less by component-level efficiencies than by a small set of dominant system drivers, notably electricity carbon intensity, hydrogen demand, and CO_2 source characteristics. Results reveal substantial trade-offs between energy input, carbon mitigation potential, and deployment robustness, highlighting that CCU–PtX pathways are inherently context-dependent rather than universally beneficial. By consolidating fragmented insights into a unified decision-oriented framework, this review clarifies where and under what conditions CCU–PtX technologies can deliver meaningful climate benefits. The findings provide actionable guidance for researchers, industry, and policymakers seeking to deploy CCU–PtX pathways strategically within net-zero energy transitions.

1. Introduction

Achieving net-zero greenhouse gas emissions requires profound transformations across energy, industrial, and transport systems, particularly in sectors where direct electrification remains technically or economically constrained. In this context, CO_2 Capture and Utilization (CCU)

How To Cite: E. Nii-Okai, B.P. Saah, A. Adebayo, G.U. Alao, A.O. Oladunni, A.C. Felix, B.O. Enobakhare. CO_2 Capture, Utilization, and Power-to-X Technologies for Sustainable Fuels and Energy Systems: A Review. *Computational Intelligence in Modern Power Systems*, 1(1):1–10, 2026. https://doi.org/10.58613/cimps111

and Power-to-X (PtX) technologies have emerged as strategically important elements of future energy systems, enabling the conversion of captured carbon dioxide and renewable electricity into low-carbon fuels, chemicals, and energy carriers. By linking carbon management with renewable power, CCU–PtX pathways provide a means to decarbonize hard-to-abate sectors while simultaneously supporting sector coupling and long-duration energy storage [1].

A rapidly growing body of literature has examined individual components of this value chain, including advances in CO_2 capture processes, catalytic and electrochemical utilization routes, and hydrogen-based fuel synthesis. However, most existing reviews remain technology-centric, focusing on isolated performance metrics such as capture efficiency, catalyst selectivity, or electrolyzer efficiency. These studies often employ inconsistent system boundaries and assumptions, making it difficult to assess the broader system-level implications of CCU–PtX deployment. As a result, reported performance indicators are frequently non-comparable, and conclusions regarding sustainability and scalability are highly context dependent [2].

This fragmentation contrasts sharply with the integrated perspective adopted in net-zero transition pathways developed by the International Energy Agency under the Paris Agreement. In these scenarios, CCU and PtX are not treated as stand-alone technologies but as interconnected elements within a larger energy system, in which renewable electricity, hydrogen production, CO_2 sources, and end-use sectors are tightly coupled. Within such a framework, overall climate performance is governed less by the peak efficiency of individual components than by system-level factors, including electricity carbon intensity, CO_2 source characteristics, and the degree of integration across conversion stages [3].

This system perspective is illustrated conceptually in Figure 1, which defines the boundaries of an integrated CCU–PtX system and traces the associated carbon and energy flows from CO_2 sources through capture, conversion, and end use. By explicitly depicting renewable electricity as a shared input to capture, electrolysis, and synthesis processes, Figure 1 emphasizes its role as the dominant control variable influencing both environmental and economic performance. The figure further clarifies what is included within the analytical boundary and what lies outside it, addressing a recurring source of inconsistency in the existing literature.

Against this backdrop, the objective of this review is to provide a system-level synthesis of CO_2 capture, utilization, and Power-to-X technologies for sustainable fuels and energy systems. Building on the integrated framework introduced in Figure 1, the review critically evaluates CCU–PtX pathways under harmonized assumptions, with particular attention to energy demand, net CO_2 reduction, and sensitivity to electricity carbon intensity. The scope encompasses major capture routes, utilization pathways, and synthetic fuel options, with an emphasis on how their interaction within integrated systems determines overall climate relevance. By moving beyond component-level assessments, this review aims to clarify where and under what conditions CCU–PtX technologies can contribute meaningfully to net-zero energy transitions.

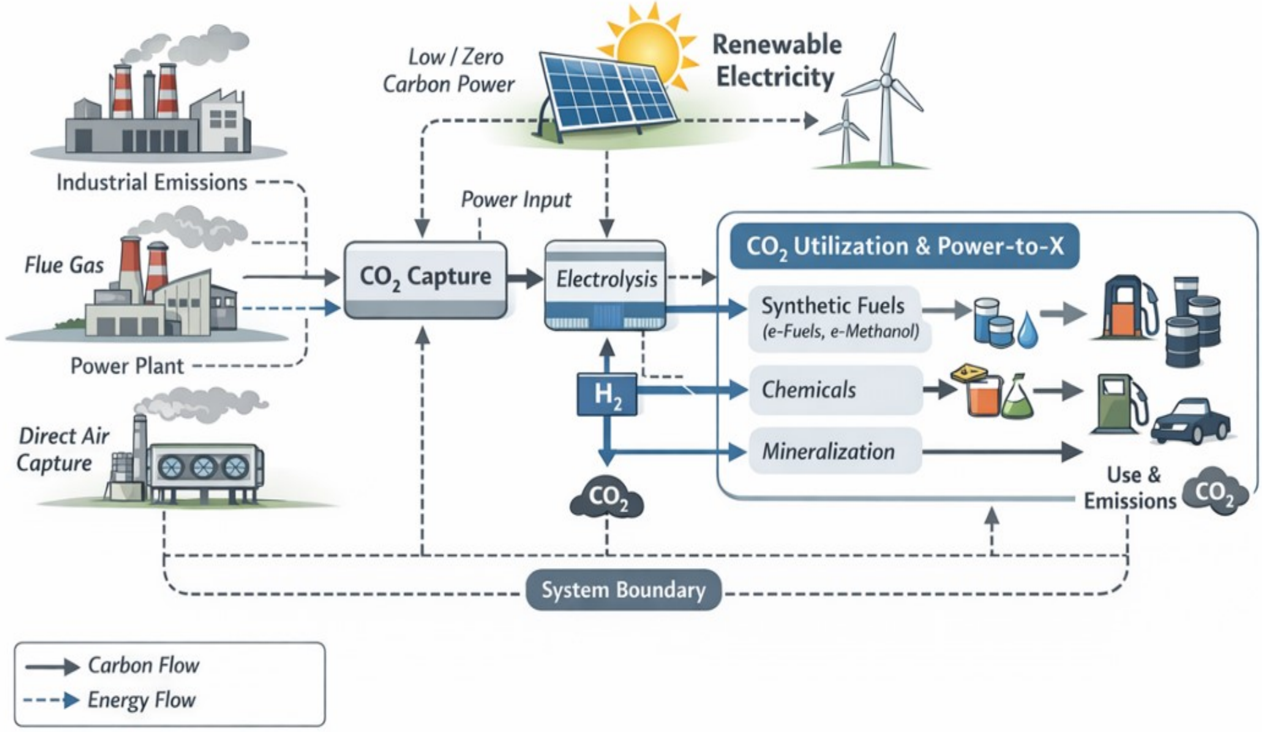


Figure 1: Integrated CCU–Power-to-X system boundary and carbon–energy flows

This presents a conceptual representation of an integrated CCU–PtX system, illustrating the flow of carbon and energy from CO_2 sources through capture, conversion, and final fuel or chemical products. Distinct from conventional schematic diagrams, the figure explicitly defines system boundaries and highlights renewable electricity as the controlling variable governing overall environmental performance. By simultaneously depicting CO_2 sources, capture processes, hydrogen production, synthesis routes, and end-use applications, the figure provides a unified framework for interpreting the diverse technologies discussed throughout the review. As such, it serves as an anchoring reference that replaces multiple descriptive diagrams and enables consistent, system-level analysis across subsequent sections.

Distinct from prior CCU and Power-to-X reviews, this work provides a harmonized, system-level and decision-oriented synthesis that evaluates integrated CCU–PtX pathways under consistent boundaries to identify when, where, and under what conditions they deliver meaningful net-zero climate benefits.

2. Literature Review

The literature on CO_2 capture, utilization, and Power-to-X technologies has expanded rapidly in response to growing interest in net-zero energy systems. While this body of work provides valuable insights into individual processes and components, it remains highly fragmented. Most review studies focus on specific segments of the CCU–PtX value chain, often employing disparate system boundaries and evaluation metrics. As a result, the collective literature offers limited guidance on the system-level performance and climate relevance of integrated CCU–PtX pathways [4].

2.1. CO_2 Capture Technologies

Existing reviews of CO_2 capture technologies predominantly assess performance as a function of separation mechanism and process configuration, with particular emphasis on post-combustion, pre-combustion, oxy-fuel combustion, and direct air capture routes. A consistent finding across these studies is the strong dependence of capture performance on CO_2 concentration and source characteristics. High-purity industrial streams are associated with comparatively low specific energy demand, whereas capture from dilute flue gases or ambient air incurs substantially higher energy penalties [5].

Despite continued advances in solvents, sorbents, and process integration, energy consumption associated with regeneration, compression, and auxiliary systems remains a dominant constraint on large-scale deployment. Moreover, scalability challengessuch as material degradation, solvent losses, and integration with existing infrastructureare frequently acknowledged but rarely evaluated in a system context. Importantly, most capture-focused reviews adopt process-level or plant-level system boundaries, limiting their ability to assess how capture energy demand affects downstream utilization or Power-to-X pathways [6].

2.2. CO_2 Utilization Pathways

Reviews of CO_2 utilization technologies typically categorize pathways into thermochemical, electrochemical, biological, and mineralization routes, with performance assessed in terms of conversion efficiency, selectivity, and product yield. A recurring theme in this literature is the trade-off between carbon efficiency and product permanence. Utilization routes that convert CO_2 into fuels or short-lived chemicals exhibit high turnover rates but limited long-term carbon storage, whereas mineralization pathways provide permanent sequestration but are constrained by market size and economic value [7].

While many studies highlight the theoretical potential of CO_2 utilization to absorb large quantities of captured carbon, fewer critically evaluate whether such pathways deliver net emissions reductions once upstream energy inputs are considered. In particular, utilization routes with high electricity or hydrogen demand may offer limited climate benefits under carbon-intensive power systems [8]. Furthermore, utilization-focused reviews often implicitly assume readily available CO_2 streams, with limited discussion of capture energy, purity requirements, or competition among end-uses.

2.3. Power-to-X Technologies

The Power-to-X literature largely centers on the conversion of renewable electricity into hydrogen via electrolysis and its subsequent transformation into synthetic fuels or chemicals. Reviews in this domain consistently identify electrolysis as the principal contributor to both energy losses and system costs, with reported efficiencies and economic projections varying widely depending on assumed electricity prices, capacity factors, and operating strategies [9].

A notable limitation of many PtX reviews is the treatment of hydrogen production and fuel synthesis as decoupled processes, despite their strong thermodynamic and operational interdependence. Temporal variability in renewable electricity supply and its implications for electrolyzer utilization and synthesis reactor operation are frequently simplified or neglected. Moreover, CO_2 supply is often treated as an external input, with capture energy requirements and constraints excluded from the analysis. This abstraction limits the applicability of PtX assessments to real-world, integrated energy systems [10].

2.4. Critical Gaps in Existing Reviews

Taken together, the existing literature reveals several persistent gaps that hinder system-level understanding of CCU–PtX pathways. First, system boundaries vary widely across reviews, ranging from gate-to-gate process analyses to partial or inconsistent life-cycle assessments. Second, sustainability metrics are non-harmonized, with energy efficiency, greenhouse gas intensity, and cost indicators often reported under incompatible assumptions. Third, CCU and PtX technologies are predominantly reviewed as separate domains, despite their inherent interdependence in net-zero energy systems [11].

These limitations are synthesized in Table 1, which compares representative CCU and Power-to-X review studies in terms of scope, technologies covered, system boundaries, sustainability metrics, and key limitations. Rather than summarizing performance data, the table highlights conceptual and methodological differences across the literature, making explicit the sources of fragmentation and non-comparability.

Unlike many existing system-level energy reviews that emphasize aggregate cost or emissions outcomes, the present review explicitly links technology performance to deployment-critical system conditions such as electricity carbon intensity, CO_2 source quality, and hydrogen demand. This framing improves decision relevance by enabling comparison of CCU–PtX pathways based on their robustness across real-world energy system contexts, rather than on idealized or technology-specific performance metrics.

Table 1: Comparison of major CO_2 Capture, Utilization, and Power-to-X review studies

Review scope	Technologies covered	System boundary	Sustainability metrics used	Key limitations identified
CO_2 capture–focused reviews	Post-combustion, pre-combustion, oxy-fuel, DAC	Process- or plant-level	Energy penalty, capture efficiency, cost	Downstream utilization and energy system impacts not considered [12]
CO_2 utilization–focused reviews	Thermochemical, electrochemical, biological, and mineralization	Partial life cycle	Conversion efficiency, yield, selectivity	Net CO_2 mitigation often not assessed [13]
Power-to-X fuel reviews	Electrolysis, synthetic fuels	Electricity-to-fuel pathway	Energy efficiency, levelized cost	CO_2 supply and capture energy are treated as fixed or external [14]
CCU reviews with LCA focus	Selected capture and utilization routes	Variable (cradle-to-gate or grave)	GHG intensity, cumulative energy demand	Strong dependence on boundary definition [15]
Integrated energy system reviews	Sector coupling, hydrogen systems	Whole energy system	System cost, emissions reduction	Limited technological resolution of CCU–PtX [16]
This review	CO_2 capture, utilization, and PtX fuels	Harmonized system-level boundary	Normalized energy efficiency and net CO_2 reduction	Focus on integration and decision relevance

By explicitly situating the present review within this landscape, Table 1 clarifies both the limitations of existing work and the distinct contribution of a harmonized, system-level assessment of CCU–PtX technologies. This integrated perspective provides the foundation for the methodological framework and comparative analysis developed in the subsequent sections.

3. Methodology

This review adopts a structured and transparent methodological approach to synthesize the literature on CO_2 capture, utilization, and Power-to-X technologies, to enablesystem-level comparability across diverse studies. Emphasis is placed on harmonizing assumptions and evaluation metrics to ensure that conclusions drawn are robust and relevant to net-zero energy system analysis.

3.1. Literature Selection Criteria

The literature considered in this review was identified through a systematic search of major scientific databases, including peer-reviewed journal articles, authoritative review papers, and selected reports from international energy and climate organizations. Keywords related to CO_2 capture, carbon utilization, electrolysis, synthetic fuels, and Power-to-X systems were combined to capture studies spanning the full CCU–PtX value chain. Priority was given to publications that report quantitative performance, cost, or environmental metrics and that explicitly state underlying assumptions. Studies focusing solely on laboratory-scale materials development without system-level relevance were excluded, as were analyses lacking sufficient methodological transparency.

The reviewed literature primarily spans publications from approximately 2010 to 2025, reflecting the period during which CCU and Power-to-X technologies matured from conceptual studies to system-level assessments relevant to net-zero energy transitions. Earlier foundational studies were included selectively where they informed methodological framing or boundary definitions.

3.2. Technology Classification Logic

To enable consistent comparison, technologies were classified according to their functional role within the CCU–PtX system rather than by disciplinary convention. CO_2 capture technologies were grouped based on source type and concentration (e.g., point sources versus ambient air), while utilization pathways were categorized by conversion mechanism and carbon retention characteristics. Power-to-X routes were classified according to the hydrogen production method and the downstream synthesis pathway. This functional classification facilitates evaluation of how individual technologies interact within integrated systems and avoids artificial separation between capture, conversion, and fuel synthesis stages [17].

3.3. Normalization of Performance, Cost, and Emissions

Reported data on energy efficiency, costs, and greenhouse gas emissions were normalized to a common set of reference units and system boundaries wherever possible. Performance metrics were expressed on an energy- or mass-specific basis, enabling comparison across different products and pathways [18]. Economic indicators were interpreted as levelized or specific costs, recognizing that absolute values vary widely across studies due to regional and temporal factors. Environmental performance was assessed primarily in terms of net CO_2 reduction, accounting for both direct and indirect emissions associated with energy inputs. Where necessary, values were recalculated or qualitatively adjusted to ensure consistency across the reviewed literature [19].

In cases where numerical normalization was not possible due to inconsistent reporting or missing data, qualitative judgments were made by comparing relative performance trends, boundary assumptions, and dominant system drivers as reported across multiple studies, rather than relying on absolute values.

3.4. Assumptions on Electricity Carbon Intensity

Given the central role of electricity in CCU–PtX systems, particular attention was paid to assumptions regarding electricity carbon intensity. Studies were interpreted within the context of low- or zero-carbon electricity supply, consistent with long-term decarbonization scenarios. Sensitivity to electricity carbon intensity was explicitly considered when comparing results, recognizing that this parameter exerts a dominant influence on both environmental and economic outcomes. By foregrounding this assumption, the review aligns its analytical framework with net-zero energy system perspectives and avoids misleading conclusions derived from fossil-based electricity inputs [20].

4. Results

4.1. Comparative Performance of CCU–PtX Pathways

When evaluated under harmonized assumptions and consistent system boundaries, clear relationships emerge between CO_2 capture energy demand, utilization efficiency, and downstream Power-to-X fuel production. Across all pathways, capture energy requirements scale strongly with CO_2 concentration, confirming that CO_2 source characteristics dominate system performance. High-purity industrial point sources consistently enable lower total energy input per unit of carbon processed, while dilute flue gas streams and direct air capture impose substantial energy penalties that propagate through utilization and fuel synthesis stages [21].

Joint consideration of capture and utilization reveals trade-offs that are obscured in technology-specific assessments. Fuel-oriented CO_2 utilization pathways typically achieve high carbon conversion efficiencies but require large quantities of hydrogen, thereby amplifying total system energy demand. Conversely, pathways with lower hydrogen intensity exhibit reduced energy input but offer less flexibility in end-use applications [8]. These interactions are explicitly captured in Figure 2, which consolidates capture, utilization, and PtX stages into a single comparative framework.

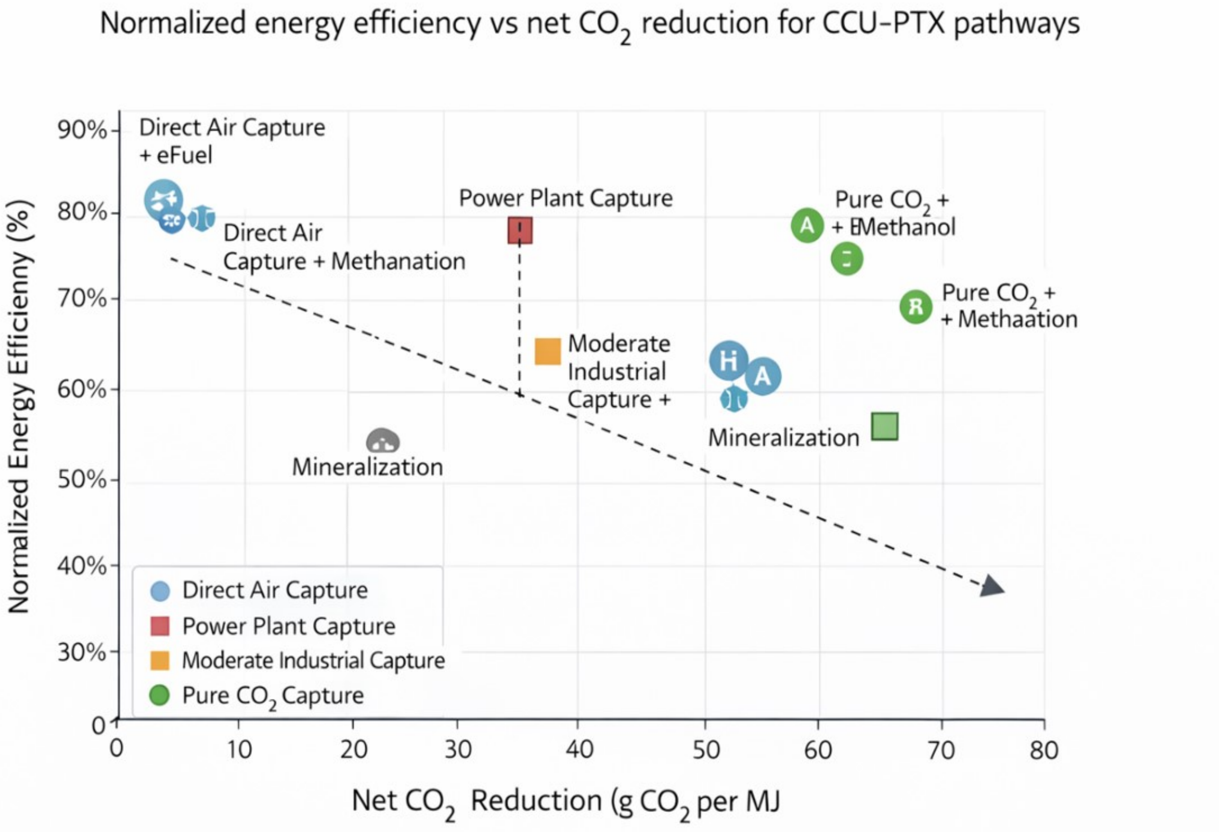


Figure 2: Normalized energy efficiency versus net CO_2 reduction for CCU–PtX pathways

Under identical assumptions for electricity supply and system boundaries, differences among PtX fuel pathways are driven less by synthesis chemistry than by hydrogen demand per unit of delivered energy [22]. This finding indicates that many discrepancies reported in the literature arise from inconsistent boundary definitions rather than from intrinsic technological advantages. By normalizing assumptions, the present analysis highlights the structural determinants of performance that are relevant at the system scale [23].

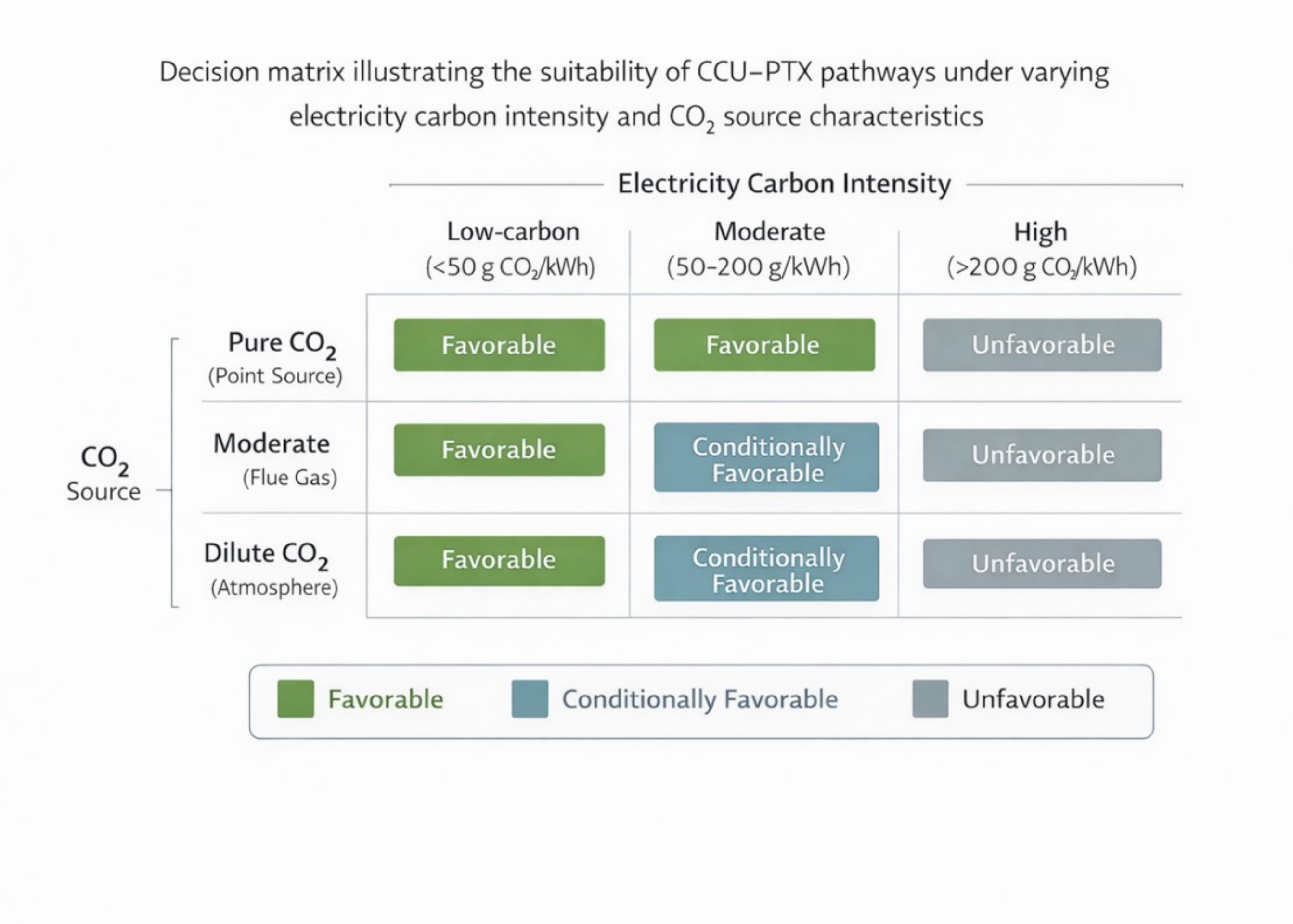
4.2. System-Level Sustainability Outcomes

System-level sustainability outcomes are most clearly understood by examining the relationship between net CO_2 reduction and total energy input, rather than isolated efficiency metrics. As illustrated in Figure 2, CCU–PtX pathways occupy a broad performance space, with some configurations achieving substantial net CO_2 reductions at moderate energy input, while others exhibit diminishing returns despite high energy consumption. Pathways combining low-energy capture with efficient hydrogen utilization consistently deliver the most favorable outcomes [24].

Sensitivity to electricity carbon intensity emerges as the dominant driver of environmental performance. Electricity-intensive pathways, particularly those involving direct air capture or hydrogen-rich synthetic fuels, show steep declines in net CO_2 benefit as electricity carbon intensity increases. In contrast, systems based on high-purity CO_2 sources display greater robustness, maintaining positive mitigation outcomes across a wider range of electricity supply conditions. These trends underscore that CCU–PtX pathways cannot be evaluated independently of the surrounding power system [25].

While Figure 2 provides a quantitative synthesis of these trade-offs, their implications for real-world deployment are further clarified in Figure 3, which translates performance outcomes into a decision-oriented framework. By mapping pathway suitability against electricity carbon intensity and CO_2 source characteristics, Figure 3 highlights that no single CCU–PtX configuration is universally optimal. Instead, pathway selection is inherently context-dependent, varying across regions, sectors, and stages of the energy transition [26].

Figure 2 presents a quantitative comparison of integrated CCU–PtX pathways by plotting normalized energy efficiency against net CO_2 reduction under harmonized assumptions. Each data point represents a complete pathway encompassing CO_2 capture, hydrogen production, and utilization or fuel synthesis. By consolidating multiple stages into a single performance space, the figure reveals trade-offs between energy input and climate benefit that are not apparent from tabulated data or component-level assessments.



Decision matrix illustrating the suitability of CCU–PTX pathways under varying electricity carbon intensity and CO_2 source characteristics

CO_2 Source	Electricity Carbon Intensity: Low-carbon (<50 g CO_2/kWh)	Moderate (50–200 g/kWh)	High (>200 g CO_2/kWh)
Pure CO_2 (Point Source)	Favorable	Favorable	Unfavorable
Moderate (Flue Gas)	Favorable	Conditionally Favorable	Unfavorable
Dilute CO_2 (Atmosphere)	Favorable	Conditionally Favorable	Unfavorable

🟩 Favorable ▨ Conditionally Favorable ▨ Unfavorable

Figure 3: Decision matrix for CCU–PtX deployment under varying system conditions

Figure 3 contextualizes the quantitative outcomes shown in Figure 2 by mapping CCU–PtX pathway suitability as a function of electricity carbon intensity and CO_2 source quality. The figure provides a decision-oriented perspective, illustrating how pathways that perform well under low-carbon electricity and high-purity CO_2 conditions may become unfavorable in less optimal system contexts. Together, Figures 2 and 3 link normalized performance metrics with deployment-relevant insights, enabling a more nuanced evaluation of CCU–PtX pathways in net-zero energy systems.

5. Discussion

The discussion below distinguishes between near-term deployment insights, which are relevant to current policy and investment decisions, and longer-term research directions, which inform future technological development and system evolution. While Figure 2 provides a quantitative synthesis of these trade-offs, their implications for real-world deployment are further clarified in Figure 3 The results presented in Section 4 demonstrate that the performance of CCU–PtX pathways cannot be meaningfully interpreted through isolated efficiency or cost metrics. Instead, outcomes are governed by a limited set of dominant system drivers and by trade-offs that only become visible when capture, utilization, and Power-to-X stages are evaluated as an integrated whole.

5.1. Dominant System Drivers

Among all parameters examined, electricity carbon intensity emerges as the single most influential determinant of environmental performance. As shown quantitatively in the results and summarized in Figure 3, electricity-intensive pathways exhibit strong sensitivity to electricity-related emissions. This effect is particularly pronounced for hydrogen-rich fuels and dilute CO_2 sources [27]. This reinforces the conclusion that CCU–PtX systems are not inherently low-carbon; their climate benefit is conditional on access to low- or near-zero-carbon electricity [28, 29].

Hydrogen availability represents a second, closely coupled driver. Hydrogen demand dominates total energy input across most PtX pathways, making both cost and availability critical constraints on scalability. Even pathways with favorable capture and utilization characteristics may face deployment limits in regions where hydrogen production is constrained by electricity supply, water availability, or infrastructure readiness. These constraints are often underrepresented in technology-focused assessments, but are central to system-level feasibility [30].

The quality and availability of CO_2 sources further shape pathway viability. High-purity point sources consistently outperform dilute streams in terms of overall energy demand and robustness to electricity carbon intensity. As illustrated in Figure 3, pathways relying on concentrated CO_2 sources remain favorable across a broader range of system conditions, whereas those dependent on dilute sources rapidly become unfavorable as electricity carbon intensity increases [31, 32]. This highlights the importance of spatial and sectoral context in CCU–PtX deployment.

5.2. Deployment-Relevant Trade-Offs

The integration of these system drivers gives rise to deployment-relevant trade-offs that are frequently obscured in component-level studies. One such trade-off is efficiency versus scalability. Pathways optimized for high conversion efficiency often rely on energy-intensive inputs or tightly coupled process configurations, which may limit their scalability under real-world electricity and hydrogen constraints. Conversely, pathways with lower efficiency but simpler integration may prove more deployable at scale, particularly in regions with abundant renewable resources [33].

A second critical trade-off concerns carbon utilization versus permanence. Fuel-oriented CCU–PtX pathways enable large-scale carbon recycling but operate within short carbon cycles, with CO_2 re-emitted upon end use. In contrast, pathways offering longer-term carbon retention, such as mineralization, exhibit greater permanence but limited flexibility and market size. Figure 3 captures this distinction by illustrating how pathway suitability depends not only on technical performance but also on the intended role within broader decarbonization strategies.

These trade-offs underscore that no single CCU–PtX pathway can be universally optimal. Instead, pathway selection must be aligned with regional energy system characteristics, sectoral demand profiles, and temporal stages of the energy transition [1, 34].

5.3. Implications for Industry and Policy

The decision matrix presented in Figure 3 translates these system-level insights into a form directly relevant to industry and policymakers. It illustrates where CCU–PtX deployment is most likely to deliver meaningful climate benefits, namely in regions with low-carbon electricity and access to concentrated CO_2 sourcesand where deployment risks yield marginal or unfavorable outcomes. This framing moves beyond binary assessments of technological feasibility and instead supports context-sensitive decision-making [35].

From an industrial perspective, the results suggest that early CCU–PtX deployment should prioritize integration with existing point-source CO_2 emitters and renewable electricity hubs, rather than diffuse or electricity-intensive configurations. For policymakers, the findings highlight the importance of aligning CCU–PtX incentives with electricity system decarbonization and hydrogen infrastructure development. Promoting utilization pathways in isolation is unlikely to deliver sustained climate benefits [36].

Finally, the interaction between CCU–PtX, carbon capture and storage (CCS), and bio-based routes warrants careful consideration. In some contexts, CCS may deliver greater near-term emissions reductions than CO_2 utilization, particularly where electricity remains carbon-intensive. Bio-based pathways may offer complementary advantages but face their own sustainability constraints. The framework articulated in Figure 3 provides a basis for evaluating these options not as competitors, but as components of a portfolio approach to net-zero transitions [37].

Overall, this discussion reinforces a central conclusion of the review: the viability of CCU–PtX technologies is fundamentally system-dependent. By explicitly linking performance outcomes to electricity carbon intensity, hydrogen availability, and CO_2 source characteristics, the decision-oriented synthesis presented here offers a pathway toward more informed and effective deployment strategies. While near-term insights emphasize deployment under existing electricity and hydrogen constraints, longer-term research directions focus on improving system integration, reducing hydrogen intensity, and expanding viable CO_2 sourcing options under deeply decarbonized power systems.

6. Conclusions

This review has evaluated CO_2 capture, utilization, and Power-to-X technologies from a system-level perspective, emphasizing their combined role in producing sustainable fuels and energy carriers. A central finding is that the climate relevance of CCU–PtX pathways is inherently context-dependent, governed primarily by electricity carbon intensity, hydrogen availability, CO_2 source characteristics, and system integration rather than by isolated component efficiencies. As a result, pathways that perform well under idealized assumptions may deliver limited or unfavorable outcomes when deployed under less suitable system conditions.

The analysis further demonstrates that effective integration across the CCU–PtX value chain is more important than incremental optimization of individual technologies. Well-integrated configurations that align capture, hydrogen production, and utilization within low-carbon electricity systems consistently outperform more efficient but poorly integrated alternatives. Consequently, CCU–PtX technologies are unlikely to serve as universal decarbonization solutions, but can play a complementary role alongside direct electrification, carbon capture and storage, and sustainable bio-based pathways.

Looking ahead, progress will depend on standardized system-level metrics, integrated pilot-scale demonstrations, and improved understanding of the role of PtX technologies in long-duration energy storage. The framework developed in this review can be extended to future comparative studies by incorporating region-specific electricity scenarios and evolving hydrogen supply pathways, providing a transferable basis for decision-relevant assessment across net-zero energy transitions.

Article Information

Disclaimer (Artificial Intelligence): The author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.), and text-to-image generators have been used during writing or editing of manuscripts.

Competing Interests: Authors have declared that no competing interests exist.

References

[1] K. R. Simonsen, D. S. Hansen, and S. Pedersen. Challenges in CO_2 transportation: Trends and perspectives. *Renewable and Sustainable Energy Reviews*, 191:114149, 2024. https://doi.org/10.1016/j.rser.2023.114149.

[2] R. Villa, S. Nieto, A. Donaire, and P. Lozano. Direct Biocatalytic Processes for CO_2 Capture as a Green Tool to Produce Value-Added Chemicals. *Molecules*, 28(14):5520, 2023. https://doi.org/10.3390/molecules28145520.

[3] I. Awwal and J. Lateef. Optimizing Urban Road Networks: A Systematic Review of Design, Control and Multimodal Integration. *Journal of Engineering Research and Reports*, 27(10):359–372, 2025. https://doi.org/10.9734/jerr/2025/v27i101678.

[4] H. Kumar, R. Sharma, A. K. Malik, A. K. Sharma, P. Kumar, and D. Singh. Advancements in carbon capture and utilization technologies: Transforming CO_2 into valuable resources for a sustainable carbon economy. *Next Energy*, 10:100476, 2026. https://doi.org/10.1016/j.nxener.2025.100476.

[5] A. Shyam, K. R. A. Ahmed, J. P. N. Kumar, S. Iniyan, and R. Goic. Path of carbon dioxide capture technologies: An overview. *Next Sustainability*, 6:100118, 2025. https://doi.org/10.1016/j.nxsust.2025.100118.

[6] A. I. Hadi, A. Yan, Y. Hu, B. Lin, T. Zhou, D. Ouyang, and J. Tang. A comprehensive review of carbon capture: From conventional to emerging electrochemical technologies. *Next Energy*, 9:100415, 2025. https://doi.org/10.1016/j.nxener.2025.100415.

[7] Y. A. Alli, O. Ejeromedoghene, T. O. Dembaremba, A. Adawi, O. A. Alimi, T. Njei, A. Bamisaye, A. Kofi, U. Q. Anene, A. M. Adewale, Z. T. Yaqub, M. E. Oladele, L. Jimoh, S. O. Oni, A. S. Ogunlaja, and B. B. Xu. Perspectives on the status and future of sustainable CO_2 conversion processes and their implementation. *Carbon Capture Science Technology*, 16:100496, 2025. https://doi.org/10.1016/j.ccst.2025.100496.

[8] Z. Wang, P. Yuan, Yu H., Q. Ma, B. Xu, D. Zhao, Z. Wang, Yuan P., . H. Yu, Q. Ma, B. Xu, and D. Zhao. Carbon Capture, Utilization and Storage: Technology, Application, and Policy. *Processes*, 13(11), 2025. https://doi.org/10.3390/pr13113414.

[9] A. R. Dahiru, A. Vuokila, and M. Huuhtanen. Recent development in Power-to-X: Part I - A review on techno-economic analysis. *Journal of Energy Storage*, 56:105861, 2022. https://doi.org/10.1016/j.est.2022.105861.

[10] L. Colelli, S. Dell'Aversano, C. Bassano, G. Vanga, K. Gallucci, and G. Vilardi. Liquid e-fuels for a sustainable future: A comprehensive review of production, regulation, and technological innovation. *Energy Conversion and Management*, 347:120529, 2026. https://doi.org/10.1016/j.enconman.2025.120529.

[11] N. Thonemann. Environmental impacts of CO_2-based chemical production: A systematic literature review and meta-analysis. *Applied Energy*, 263:114599, 2020. https://doi.org/10.1016/j.apenergy.2020.114599.

[12] M. Seyyedattar and S. Zendehboudi. Carbon capture and storage: A comprehensive review on current trends, techniques, and future prospects in North America. *Fuel*, 407:137276, 2026. https://doi.org/10.1016/j.fuel.2025.137276.

[13] C. Kim, C.-J. Yoo, H.-S. Oh, B. K. Min, and U. Lee. Review of carbon dioxide utilization technologies and their potential for industrial application. *Journal of CO_2 Utilization*, 65:102239, 2022. https://doi.org/10.1016/j.jcou.2022.102239.

[14] A. S. Oyewo, G. Lopez, M. ElSayed, T. Galimova, and C. Breyer. Power-to-X Economy: Green e-hydrogen, e-fuels, e-chemicals, and e-materials opportunities in Africa. *Energy Reports*, 12:2026–2048, 2024. https://doi.org/10.1016/j.egyr.2024.08.011.

[15] L. J. Müller, A. Kätelhön, M. Bachmann, A. Zimmermann, A. Sternberg, and A. Bardow. A Guideline for Life Cycle Assessment of Carbon Capture and Utilization. *Frontiers in Energy Research*, 8, 2020. https://doi.org/10.3389/fenrg.2020.00015.

[16] S. Faisal, C. Gao, S. Faisal, and C. Gao. A Comprehensive Review of Integrated Energy Systems Considering Power-to-Gas Technology. *Energies*, 17(18), 2024. https://doi.org/10.3390/en17184551.

[17] A. D. N. Kamkeng, M. Wang, J. Hu, W. Du, and F. Qian. Transformation technologies for CO_2 utilisation: Current status, challenges and future prospects. *Chemical Engineering Journal*, 409:128138, 2021. https://doi.org/10.1016/j.cej.2020.128138.

[18] J. Lateef and I. M. Awwal. Evolution and Performance of Post-Tensioned Concrete Bridge Systems: A Systematic Critical Review of the Disconnect between Technological Advancement and Practical Implementation. *Asian Journal of Current Research*, 10(4): 304–319, 2025. https://doi.org/10.56557/ajocr/2025/v10i49937.

[19] N. N. Abu Bakar, M. Y. Hassan, H. Abdullah, H. A. Rahman, M. P. Abdullah, F. Hussin, and M. Bandi. Energy efficiency index as an indicator for measuring building energy performance: A review. *Renewable and Sustainable Energy Reviews*, 44:1–11, 2015. doi: https://doi.org/10.1016/j.rser.2014.12.018.

[20] P. Cheekatamarla. Role of On-Site Generation in Carbon Emissions and Utility Bill Savings under Different Electric Grid Scenarios. *Energies*, 15(10), 2022. https://doi.org/10.3390/en15103477.

[21] M. H. Rasool and S. A. Moiz Hashmi. *Carbon capture and storage: An evidence-based review of its limitations and missed promises*. Petroleum Research, 2025. https://doi.org/10.1016/j.ptlrs.2025.09.005.

[22] J. Lateef and I. M. Awwal. A Narrative Review of Recent Advances in Accelerated Bridge Construction: Materials, Methods, and Implementation Challenges. *Journal of Basic and Applied Research International*, 31(6):99–111, 2025. https://doi.org/10.56557/jobari/2025/v31i69985.

[23] P. Diesing, G. Lopez, P. Blechinger, and C. Breyer. From knowledge gaps to technological maturity: A comparative review of pathways to deep emission reduction for energy-intensive industries. *Renewable and Sustainable Energy Reviews*, 208:115023, 2025. https://doi.org/10.1016/j.rser.2024.115023.

[24] L. Desport and S. Selosse. An overview of CO_2 capture and utilization in energy models. *Resources, Conservation and Recycling*, 180: 106150, 2022. https://doi.org/10.1016/j.resconrec.2021.106150.

[25] W. Ziarkash, S. Bünning, A. Bensmann, E. Baake, and R. Hanke-Rauschenbach. A comparative analysis of low-CO_2 steam generation technologies. *Energy Conversion and Management: X*, 26:101013, 2025. https://doi.org/10.1016/j.ecmx.2025.101013.

[26] K. Wang, L. Ouyang, Y. Wang, K. Wang, L. Ouyang, and Y. Wang. Study of Energy Transition Paths and the Impact of Carbon Emissions under the Dual Carbon Target. *Sustainability*, 15(3), 2023. https://doi.org/10.3390/su15031967.

[27] I. J. Opara, J. Lateef, E. Nii-Okai, B. P. Saah, E. K. Mensah, G. F. O. Wiafe, and A. Olayode. Digital Resilience in Construction Projects: A Narrative Review of Data Governance, BIM, and Real-Time Decision Support Systems. *Journal of Management, and Development Research*, 2(2):117–124, 2025. https://doi.org/10.69739/jmdr.v2i2.1129.

[28] G. Papachristos. Household electricity consumption and CO_2 emissions in the Netherlands: A model-based analysis. *Energy and Buildings*, 86:403–414, 2015. https://doi.org/10.1016/j.enbuild.2014.09.077.

[29] X. Zhang, Q. Zhu, X. Zhang, X. Zhang, Q. Zhu, and X. Zhang. Carbon Emission Intensity of Final Electricity Consumption: Assessment and Decomposition of Regional Power Grids in China from 2005 to 2020. *Sustainability*, 15(13), 2023. https://doi.org/10.3390/su15139946.

[30] M. H. Kebede, F. Ustolin, S. Völler, M. Korpås, and I. Oleinikova. System integration of large-scale green hydrogen production: Conceptualization, challenges, and opportunities. *Energy Conversion and Management: X*, 28:101365, 2025. https://doi.org/10.1016/j.ecmx.2025.101365.

[31] K. Aghaee. Carbon capture, utilization, and storage for sustainable construction: Insights into CO_2 mixing, curing, and mineralization. *Carbon Capture Science Technology*, 17:100503, 2025. https://doi.org/10.1016/j.ccst.2025.100503.

[32] F. Sabatino, A. Grimm, F. Gallucci, M. van Sint Annaland, G. J. Kramer, and M. Gazzani. A comparative energy and costs assessment and optimization for direct air capture technologies. *Joule*, 5(8):2047–2076, 2021. https://doi.org/10.1016/j.joule.2021.05.023.

[33] Anis ur Rehman., M. J. Sanjari, R. M. Elavarasan, and T. Jamal. Sustainability-aligned pathways for energy transition: A review of low-carbon energy network solutions. *Renewable and Sustainable Energy Reviews*, 226:116428, 2026. https://doi.org/10.1016/j.rser.2025.116428.

[34] A. G. Olabi, T. Wilberforce, K. Elsaid, E. T. Sayed, H. M. Maghrabie, and M. A. Abdelkareem. Large scale application of carbon capture to process industries – A review. *Journal of Cleaner Production*, 362:132300, 2022. https://doi.org/10.1016/j.jclepro.2022.132300.

[35] G. Müller, F. Kullmann, J. Linssen, and D. Stolten. The costs of future energy technologies: A comprehensive review of power-to-X processes. *Journal of CO_2 Utilization*, 92:103019, 2025. https://doi.org/10.1016/j.jcou.2025.103019.

[36] J. A. Garcia, M. Villen-Guzman, J. M. Rodriguez-Maroto, J. M. Paz-Garcia, J. A. Garcia, M. Villen-Guzman, J. M. Rodriguez-Maroto, and J. M. Paz-Garcia. Comparing CO_2 Storage and Utilization: Enhancing Sustainability through Renewable Energy Integration. *Sustainability*, 16(15), 2024. https://doi.org/10.3390/su16156639.

[37] W. Y. Cheah, T. C. Ling, J. C. Juan, D.-J. Lee, J.-S. Chang, and P. L. Show. Biorefineries of carbon dioxide: From carbon capture and storage (CCS) to bioenergies production. *Bioresource Technology*, 215:346–356, 2016. https://doi.org/10.1016/j.biortech.2016.04.019.