Technology Review for Carbon Neutrality

Review

Catalytic CO_2 utilization in the power sector: an engineering framework for project deployment and techno-economic assessment

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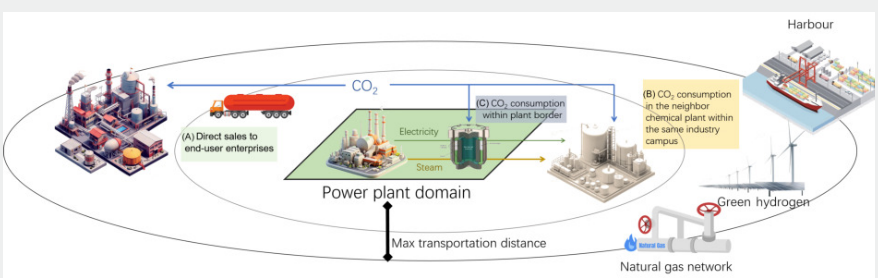
ABSTRACT

To address pressing CO_2 mitigation needs in the power sector, this review provides a pragmatic engineering framework for deploying catalytic CO_2 utilization (CCU) technologies. Synthesizing data from a global portfolio of industrial projects across ten major routes—from e-methanol to molten salt electrolysis—we critically address the operational constraint of excluding hazardous chemical units from power plant sites. We introduce a novel three-tiered deployment framework to resolve this: (A) capture-for-sale to external offtakers, (B) near-plant modular conversion into transportable products, and (C) on-site coupled production of low-hazard materials. Using a unified techno-economic model, we perform a cross-route comparison to identify critical cost drivers and profitability thresholds. Our analysis concludes that a portfolio approach is essential, guided by local resource endowments and market access. This review provides an actionable, data-driven guide for utilities, investors, and policymakers, bridging the gap between catalytic science and bankable, large-scale project deployment.



KEYWORDS

Power sector; CO_2 utilization; techno-economic analysis; project deployment framework; demonstration projects

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1. Introduction

The imperative to mitigate climate change has placed the global power sector at the epicenter of the energy transition. As the largest single source of anthropogenic CO_2 emissions, its decarbonization is paramount[1]. While the deployment of renewable generation is accelerating, thermal power plants remain a critical component of energy security in many regions, necessitating robust strategies for carbon management. Carbon capture, utilization, and storage (CCUS) has emerged as a key pillar in this effort. However, the paradigm is shifting from a singular focus on geological storage (CCS) towards a more integrated vision of a circular carbon economy, where captured CO_2 is valorized as a feedstock for fuels, chemicals, and materials (CCU)[2,3].

The power sector is uniquely positioned to anchor this new economy. It offers large, concentrated streams of CO_2 and is increasingly the primary source of low-cost, low-carbon electricity required for electro-intensive conversion processes. This dual role—as both a major carbon source and a key enabler of its conversion—creates a powerful nexus for innovation.

A substantial body of academic literature has meticulously detailed the scientific and engineering fundamentals of various CCU pathways. Comprehensive reviews have covered electrochemical CO_2 reduction (CO_2RR) from catalyst design to reactor engineering[4,5], high-temperature solid-oxide co-electrolysis (SOEC) of CO_2/H_2O to syngas[6,7], and techno-economic analyses (TEAs) of specific products like e-methanol and e-methane[8,9]. However, a critical gap persists between laboratory-scale advances and real-world project deployment, particularly from the perspective of a power utility. Three key deficiencies limit the translation of academic research into actionable industrial strategy:

1) **Lack of a power-sector-centric siting framework:** Most analyses overlook the stringent safety, regulatory, and operational constraints of power plants[10]. The fundamental principle that power utilities are not, and do not wish to become, chemical plant operators is often ignored. A pragmatic framework that delineates on-site versus off-site activities is essential for realistic project planning.

2) **Absence of a unified, cross-route economic metric:** Existing TEAs, while valuable, are often pathway-specific and use disparate assumptions for key variables like electricity price, capital costs, and logistics. This makes direct, "apples-to-apples" comparisons for investment decision-making exceedingly difficult.

3) **Unsystematized engineering heuristics:** The critical success factors of pioneering projects are often documented in press releases, government reports, and corporate presentations[11,12], but are rarely synthesized into a coherent set of engineering best practices. The tacit knowledge regarding CO_2 purity[13], logistics radii[14], and downstream market integration needs to be systematically codified.

This review addresses these gaps by proposing and validating a novel, power-sector-centric framework for evaluating and deploying catalytic CO_2 utilization technologies. We structure our analysis around three practical deployment archetypes: **(A) capture-for-sale**, **(B) near-plant modular conversion**, and **(C) on-site coupled production**. Within this framework, our contribution is fourfold: (i) we synthesize the project landscape for ten key catalytic routes, identifying the common endowments of successful demonstrations; (ii) we introduce a set of simplified, unified economic metrics grounded in Chinese market data (RMB) to facilitate rapid, transparent comparisons; (iii) we distill replicable engineering practices for integrating these routes within a realistic "plant-outside, park-inside" organizational model; and (iv) we offer differentiated, actionable recommendations for technology deployment based on a utility's specific resource profile and strategic objectives.

Our methodology integrates a systematic review of academic and institutional literature (2020–2025) with a comprehensive analysis of over 50 publicly documented industrial projects. By grounding scientific potential in the soil of economic reality and engineering pragmatism, this review provides a robust and replicable framework for decision-makers in the power sector, as well as for researchers, investors, and policymakers navigating the complex landscape of the emerging circular carbon economy.

2. Catalytic pathways and project landscape

This section systematically evaluates ten prominent catalytic CO_2 utilization routes. For each pathway, we present the core chemical principles, summarize key engineering challenges, analyze representative international and Chinese projects, and distill critical lessons for successful deployment. A comprehensive compilation of the projects discussed in this review, including detailed information on stakeholders, funding, scale, and specific source links, is provided in **Table S1** in the Electronic Supplementary Material (ESM).

2.1 CO_2 hydrogenation to methanol (e-methanol)

2.1.1 Technical principles

The synthesis of methanol from CO_2 and H_2 is governed by three principal equilibrium reactions: direct CO_2 hydrogenation ($CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$), CO hydrogenation ($CO + 2H_2 \rightleftharpoons CH_3OH$), and the reverse water–gas shift (RWGS) reaction ($CO_2 + H_2 \rightleftharpoons CO + H_2O$). The process is highly exothermic and equilibrium-limited, necessitating high pressures (50–100 bar), moderate temperatures (200–300 °C), and a recycle loop to achieve viable conversions[15]. The workhorse catalyst is a copper/zinc oxide/alumina ($Cu/ZnO/Al_2O_3$) composite, where the active sites are believed to be Cu-ZnO interfaces[16]. Key industrial challenges include managing the large heat of reaction, preventing catalyst deactivation by sintering and water, and achieving high single-pass conversion to minimize recycle costs. However, one of the most unforgiving operational constraints is feedstock purity. Because the active Cu-sites are highly susceptible to poisoning by sulfur and halides common in power plant flue gases, purity is not merely a specification but a primary financial risk. Project teams must budget significant resources for robust, upstream guard beds and redundant real-time gas analysis. In an industrial context, a spike in off-spec CO_2 can irreversibly destroy a multi-million dollar catalyst charge in hours, rendering average purity metrics meaningless. Recent research focuses on alternative catalysts like indium oxide (In_2O_3)-based systems, which show higher selectivity and water tolerance[17].

2.1.2 Project landscape and strategic insights

Internationally, projects are increasingly targeting premium green fuel markets. The flagship **Kassø e-methanol facility** in Denmark (42 kt/a), which entered commercial operation in 2025, is a prime example. It integrates solar power, electrolytic hydrogen, and biogenic CO_2 to produce renewable fuel of non-biological origin (RFNBO) for the marine sector, with Maersk as a key offtaker[12,18]. This model is driven by policies like the EU's FuelEU Maritime regulation, which mandates increasing shares of green fuels[19]. Other notable projects like HIF Global's **Haru Oni** in Chile leverage exceptional wind resources to produce e-gasoline via a methanol intermediate for customers like Porsche.

In China, the strategic focus is markedly different, prioritizing industrial symbiosis and cost reduction over green premiums. The **Shunli plant** in Anyang (110 kt/a) exemplifies this by utilizing hydrogen-rich coke-oven gas from an adjacent steel plant, drastically reducing the cost of hydrogen, the primary cost driver[20]. Similarly, the **Sailboat Petrochemical** plant in Lianyungang (100 kt/a) is embedded within a massive integrated refinery and petrochemical complex. It uses by-product hydrogen and captured CO_2 to produce methanol that is consumed on-site as a feedstock for producing olefins and other chemicals, thus eliminating transportation costs and market volatility[21]. These projects underscore a key lesson: the economic viability of CO_2-to-methanol is less about the core synthesis technology and more about the clever integration of low-cost feedstocks (H_2, CO_2) and captive downstream markets.

2.2 CO_2 methanation (Sabatier reaction)

2.2.1 Technical principles

The Sabatier reaction ($CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$) is a highly exothermic process ($\Delta H^\circ_{298} \approx -165$ kJ/mol) that converts CO_2 and H_2 into synthetic natural gas (SNG). It is technologically mature, typically using robust and inexpensive Ni-based catalysts on supports like Al_2O_3 or CeO_2 at temperatures of 300–400 °C[22]. The primary engineering challenges are thermal management to prevent catalyst sintering and runaway reactions, and the need for high conversion to meet stringent gas grid specifications for methane purity and residual H_2 content. Modern reactor designs often employ isothermal or micro-channel configurations to enhance heat removal[23].

2.2.2 Project landscape and strategic insights

Europe has a rich portfolio of Power-to-Gas (P2G) demonstration projects driven by the need for large-scale, long-duration energy storage. The pioneering **Audi e-gas plant** in Werlte, Germany (6 MW, 2013), established the feasibility of industrial-scale grid injection[24]. Subsequent projects like the EU's **STORE&GO** initiative and France's **Jupiter 1000** have advanced the technology, focusing on dynamic operation with intermittent renewables and coupling with various CO_2 sources, including biogas plants and industrial emitters[25,26]. The business model relies on monetizing multiple value streams: grid balancing services, renewable gas certificates, and utilization of waste heat.

In China, by contrast, large-scale catalytic methanation projects are notably scarce. The few documented examples, such as the **Jinyun P2G demonstration** in Zhejiang, are small-scale and focused on specific local applications like rural energy supply from biomass[27]. This disparity can be attributed to several factors: China's natural gas pricing structure, a less developed market for green gas certificates, and a strategic policy focus on hydrogen itself, as well as methanol and ammonia, as primary energy vectors over SNG[28]. The lesson for the power sector is that the methanation route's viability is less a technical question and more a function of regional energy policy and gas market structure.

2.3 SOEC Co-electrolysis to Syngas

2.3.1 Technical principles

Solid-oxide co-electrolysis (SOEC) of CO_2 and steam ($CO_2 + H_2O \rightarrow CO + H_2 + O_2$) at high temperatures (700–850 °C) is a highly efficient one-step process to produce tunable syngas. By leveraging high-temperature waste heat to provide a significant portion of the energy required for the endothermic reaction, SOEC systems can achieve electrical efficiencies significantly higher than low-temperature electrolysis plus a separate RWGS unit[29]. The key challenges are long-term stack durability, robust sealing at high temperatures, and tolerance to impurities (e.g., sulfur) present in industrial CO_2 streams[30].

2.3.2 Project landscape and strategic insights

Demonstrations are rapidly scaling from kilowatts to megawatts. In Europe, the **MegaSyn** project is deploying a MW-scale co-electrolysis unit at an OMV refinery in Austria to validate performance in an industrial environment[31]. In Germany, **Sunfire** and **KIT** are integrating co-electrolysis into a complete Power-to-Liquid pilot plant[32]. In China, development is progressing from kW-scale laboratory systems to industrial pilots. The **Shanghai Institute of Applied Physics (SINAP)** has successfully operated a 10 kW system with tunable H_2/CO ratios and stable operation, a key milestone[33]. At the industrial pilot level, a 30 kW skid-mounted system is being developed by **Beijing Swete** for Baosteel to produce reducing gas from steel mill off-gases[34]. This indicates a global convergence on steel and refining as prime sectors for SOEC integration, where both waste heat and CO_2 are readily available.

2.4 Power-to-Liquid (PtL) fuels (FT/MTG routes)

2.4.1 Technical principles

PtL routes convert CO_2 and green hydrogen into liquid hydrocarbon fuels (e-SAF, e-diesel, e-naphtha) via a syngas intermediate, followed by either Fischer-Tropsch (FT) or Methanol-to-Gasoline/Jet (MTG/J) synthesis[35]. These multi-step, capital-intensive processes are justified by the high value of their products, particularly for decarbonizing aviation. Key engineering challenges include precise thermal management of the highly exothermic FT reaction, catalyst stability, and extensive downstream processing (hydrocracking, isomerization) to meet stringent fuel specifications.

2.4.2 Project landscape and strategic insights

The field has recently transitioned from pilot to first-of-a-kind (FOAK) commercial plants. In Germany, **INERATEC's ERA ONE** plant (2,500 t/a) came online in 2025[11]. In the US, **Infinium's Pathfinder** project in Texas began commercial operation in 2024, supplying e-diesel to Amazon[36]. Now, China is entering the race with unprecedented scale. **SPIC's "Hydrogen Green Jianglong"** project in Heilongjiang is a flagship example, coupling 3.5 GW of dedicated wind power with a planned 400 kt/a e-SAF and 400 kt/a e-methanol facility, starting with a 10 kt/a pilot[37]. The common thread is the need for vast amounts of low-cost renewable electricity and strategic partnerships with offtakers (e.g., airlines) to de-risk the investment.

2.5 Cyclic carbonates and poly(ether/ester carbonate) polyols (PPC/polyols)

2.5.1 Technical principles

These routes represent mature (technology readiness level (TRL) 8-9), commercially deployed technologies where CO_2 is chemically incorporated into polymer structures.

1) **Cyclic carbonates (EC/PC):** Formed via the atom-economical cycloaddition of CO_2 to epoxides (ethylene oxide or propylene oxide): $C_2H_4O + CO_2 \rightarrow C_3H_4O_3$. The reaction is typically catalyzed by homogenous catalysts like quaternary ammonium salts or metal complexes at mild conditions (80–200 °C, 1–5 MPa)[38,39]. While homogeneous systems are historically dominant, they incur significant operational costs due to the energy-intensive separation of catalysts from high-boiling products. Consequently, recent industrial deployments are pivoting toward **heterogeneous catalysts** (e.g., ionic liquids immobilized on polymers or MOFs) to enable simplified filtration or fixed-bed operations. Furthermore, the feedstock landscape is diversifying: beyond the direct epoxide route, the transesterification of CO_2-derived urea with polyols (e.g., ethylene glycol derived from coal or biomass) is emerging as a competitive pathway, particularly in regions like China where "Coal-to-Chemicals" capacity provides a cost-advantaged alternative to oil-based epoxides. The products, ethylene carbonate (EC) and propylene carbonate (PC), are essential high-permittivity solvents in lithium-ion battery electrolytes.

2) **PPC/polyols:** The ring-opening copolymerization (ROCOP) of CO_2 and epoxides, using catalysts like double-metal cyanides (DMCs) or salen complexes, produces poly(propylene carbonate) (PPC) or polyether-carbonate polyols[40]. These polyols, containing up to 20–40% CO_2 by weight, are valuable precursors for polyurethanes (PU), used in foams, coatings, and elastomers.

The primary challenge is not the chemistry itself but achieving the ultra-high purity required for battery applications (sub-ppm levels of water and metals) and managing the cost and availability of the epoxide feedstock.

2.5.2 Project landscape and strategic insights

This is a sector where industrialization is well-established globally, and the focus is on scaling up to meet the explosive demand from the electric vehicle and energy storage markets. International leaders include **Covestro** (Germany), with its cardyon® brand of CO_2-based polyols produced at a 5 kt/a plant in Dormagen[41], and **Aramco Performance Materials**, which markets the Converge® polyol technology.

China has rapidly become a dominant force in this area, driven by its world-leading battery industry. Companies like **Satellite Chemical** (Lianyungang) and **Hualu Hengsheng** (Dezhou) have commissioned massive complexes with capacities exceeding 150 kt/a and 300 kt/a, respectively, for battery-grade carbonate solvents[42,43]. A landmark project is the **CSPC (Shell-CNOOC JV)** expansion in Daya Bay, which includes a 320 kt/a carbonate solvents unit[44].

The strategic insight for the power sector is clear: this is a prime opportunity for a **Type A**

"capture-for-sale" model. The technology is proven, the market is large and growing, and the chemical producers are sophisticated offtakers. A power plant's role is to provide a reliable, specification-compliant stream of CO_2 to a nearby chemical park, creating a low-risk, high-volume offtake route. The profitability is primarily driven by the price spread between the final product and the epoxide feedstock, with CO_2 acting as a low-cost C1 source that provides a competitive edge.

2.6 Emerging electrochemical and novel routes

This category includes pathways at earlier stages of development (TRL 4-7) but with significant long-term potential due to their modularity, electrification, and product diversity.

1) **Low-temperature electro-CO:** This route uses electricity to convert CO_2 to CO at ambient conditions. Companies like **Twelve** (USA) and **Carbon Energy** (China) are scaling up this technology from pilot to demonstration scale, targeting integration into e-fuels and chemicals production[45–47].

2) **Electro-formic acid:** This is one of the most promising direct electrochemical routes due to its relatively high efficiency and the production of a stable, liquid product. **OCOchem** (USA) has commissioned a multi-unit pilot plant, and several Chinese startups are entering the hundred-ton scale[48]. The product has existing markets and potential as a hydrogen carrier[49].

3) **Molten carbonate electrolysis (MCE) to solid carbon:** This high-temperature (~750 °C) process directly reduces CO_2 into high-value solid carbon materials like carbon nanotubes (CNTs) or graphene nanocarbons, with pure oxygen as a byproduct[50]. It is being commercialized by startups like **SkyNano** (USA) and has seen its first industrial demonstration in Shanxi, China, targeting the lucrative market for battery conductive additives[51,52]. Its potential for on-site (Type C) deployment is a unique advantage.

4) **Plasma/microwave conversion:** These routes use electrical discharges to create a non-equilibrium plasma that dissociates CO_2 into CO and O_2 with very fast response time. While energy efficiency is still a major challenge, industrial pilots are emerging, such as **D-CRBN's** project at the ArcelorMittal steel plant in Belgium, which couples a plasma reactor directly to a CO_2 capture unit[53].

Unlike the thermal baseload systems required for methanol or FT synthesis, these emerging routes are defined by their modularity and rapid response time, making them uniquely suited for coupling with intermittent renewables.

In the realm of Low-Temperature Electrolysis, the landscape is moving from kW-scale pilots to MW-scale demonstrations. In the US, Twelve has pioneered the commercialization of PEM-based CO_2 electrolyzers, deploying their "Opus" system to produce e-jet fuel intermediates. Their strategy focuses on high current density and compact stack design to reduce CAPEX. In China, Carbon Energy (Beijing) has commissioned a 10 MW-scale demonstration, validating the stability of large-area electrodes in industrial environments. For power utilities, these "black-box" electrolyzers offer a distinct advantage: they operate similarly to battery storage systems, capable of ramp-rates that thermal reactors cannot match, thus serving a dual function of carbon utilization and grid balancing.

For Molten Carbonate Electrolysis (MCE), the strategic value lies in the physical state of the product. Startups like SkyNano (USA) and recent pilots in Shanxi, China, are demonstrating the direct conversion of flue gas CO_2 into solid carbon nanotubes (CNTs). This presents a unique operational advantage: unlike gaseous CO or liquid fuels, solid carbon is non-hazardous, chemically inert, and easy to store. This characteristic potentially allows for safe integration directly within strictly regulated power plant boundaries, decoupling production from the immediate need for pipeline infrastructure.

The overarching insight for this sector is that while energy efficiency remains a challenge, the simplicity of the balance-of-plant (BoP)—avoiding high-pressure loops or intense heating—positions these routes as strong candidates for future decentralized and modular deployment models.

3. A framework for power sector integration

To translate technological potential into viable projects, a framework is needed that respects the unique operational context of the power sector. The central, non-negotiable constraint is the avoidance of introducing new, large-scale hazardous chemical processing units and storage facilities within the power plant's established fence line.

3.1 Fence-line boundary condition

Power plants are highly regulated, safety-critical infrastructures. In recent years, a strong trend in the industry, particularly in China, has been to reduce on-site chemical hazards. Proposing to build a multi-hundred-ton methanol synthesis loop or a high-pressure Fischer-Tropsch reactor within the plant boundary is operationally, regulatorily, and culturally unfeasible[10]. Therefore, any viable CCU strategy must physically segregate chemical conversion from power generation. Our framework is built on this principle, as depicted in Fig. 1.

3.2 Deployment archetypes: Types A, B, and C

Beyond the operational boundary constraints, this framework is designed to resolve the classic "chicken-and-egg" dilemma of CCUS infrastructure. Conventionally, large-scale conversion projects require low-cost CO_2 via pipelines, yet the financing of such pipelines is often stalled by the lack of guaranteed, high-volume offtake from operational plants. In this context, the proposed archetypes offer a strategic decoupling:

1) **Type A: capture-for-sale.** The power plant invests in and operates the CO_2 capture, purification, and compression/liquefaction island. The final product—pipeline-spec or liquid CO_2—is sold "over the fence" to an adjacent or nearby industrial user under a long-term supply agreement.

2) **Type B: near-plant modular conversion.** Modular, skid-mounted conversion units are located just outside the power plant's fence. The power plant supplies CO_2 via a short pipeline and low-cost electricity via a direct PPA.

3) **Type C: on-site coupled production.** This is reserved for processes with an intrinsically low hazard profile. The prime example is molten carbonate electrolysis (MCE) to solid carbon.

While Type A (capture-for-sale) represents the mature end-state requiring established logistics, Type B (near-plant modular) and Type C (on-site coupled) serve as critical "infrastructure-independent" entry points. By eliminating the reliance on long-distance transport networks, these models allow power utilities to deploy capital and validate technologies immediately, effectively bridging the gap until regional CO_2 pipeline networks are financially viable.

3.3 Unified metrics for cross-route comparison

To enable consistent evaluation, we propose a minimal set of metrics: levelized cost of product (LCOX), unit energy intensity, breakeven product price, and marginal revenue per tonne of CO_2.

4. Comparative techno-economic assessment

Techno-economic analysis underscores that hydrogen cost is the dominant variable in e-fuel production, often accounting for 60%–70% of the total levelized cost. Our assessment reveals a critical divergence between "academic" and "industrial" viability. While long-term models assume low-cost electrolytic hydrogen (< 2/kg), current market realities render fully green routes economically challenging without massive subsidies. Therefore, from a project-execution standpoint, leveraging lower-cost hydrogen vectors is a non-negotiable bridging strategy. Industrial by-product hydrogen (e.g., hydrogen-rich off-gases from coke ovens, propane dehydrogenation (PDH) units, or chlor-alkali plants) and "blue" hydrogen (steam methane reforming (SMR) coupled with CCS) offer immediate feedstocks at competitive prices (1.5–2.5/kg). Deploying CCU assets with these "grey" or "blue" inputs allows utilities to validate technology and secure offtake contracts today. This strategy effectively decouples the investment in the CO_2 utilization asset from the

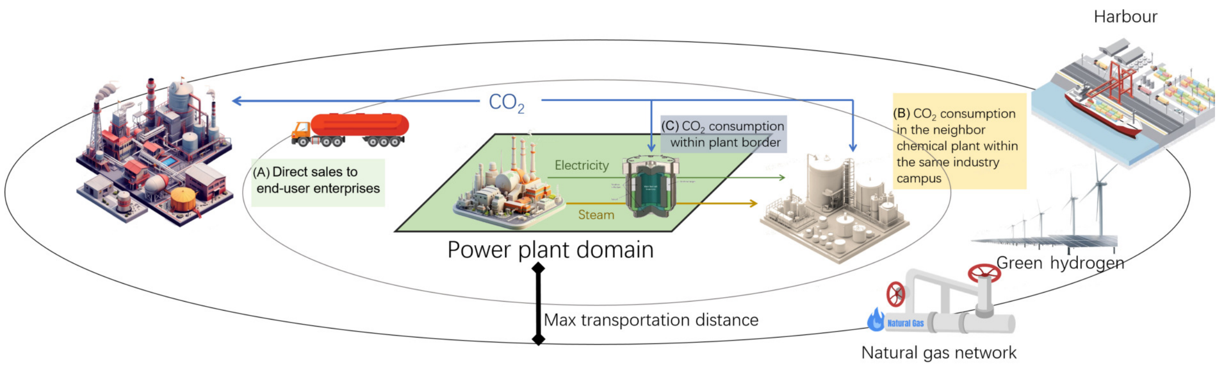

Fig. 1. Schematic of the three-tiered deployment framework for CO_2 utilization in the power sector, illustrating the distinct operational boundaries. A: capture-for-sale, where purified CO_2 is transported to external end-users. B: near-plant modular conversion, where CO_2 is processed in an adjacent industrial park. C: on-site coupled production, where low-hazard processes are integrated within or adjacent to the power plant's boundary.

volatility of the green hydrogen market, allowing for a seamless feedstock transition as electrolyzer economics mature. For the cyclic carbonates (EC/PC) pathway, the techno-economic analysis (TEA) reveals two critical sensitivity factors often overlooked in simplified models: catalyst separation costs and feedstock volatility. For homogeneous systems, the distillation duty required for catalyst recovery can degrade the product and inflate operating expense (OpEX). More critically, while switching to green or coal-derived polyols reduces carbon footprint, it exposes projects to distinct price fluctuation cycles (e.g., coal or corn markets) that differ significantly from the relatively dampened volatility of the petrochemical epoxide chain.

Applying our unified framework, we now present a comparative techno-economic assessment of the key routes, grounded in Chinese market conditions (RMB basis). Table 1 summarizes the key findings. Detailed breakdowns of the techno-economic analyses for each route, including power sector opportunity commentary, current cost estimations, investment return analyses, and deployment boundary conditions, are presented in **Table S2** in the ESM.

5. Strategic outlook and recommendations

5.1 For utilities with abundant, low-cost renewable resources

1) **Short-term (1–3 years):** Initiate Type B pilot projects for SOEC co-electrolysis and e-methanol (1–10 MW scale).

2) **Mid-term (3–7 years):** Scale up the most promising route to a first-commercial plant (100+ MW).

5.2 For utilities in industrial clusters

1) **Short-term (1–3 years):** Immediately pursue Type A "capture-for-sale" opportunities, targeting producers of cyclic carbonates, polyols, or aromatics.

2) **Mid-term (3–7 years):** Explore Type B projects that leverage existing park infrastructure, such as an electro-formate or electro-CO unit.

5.3 For all utilities: building foundational capabilities

1) **Invest in capture technology maturation:** Pilot next-generation capture technologies to drive down costs.

2) **Develop commercial expertise:** Build teams capable of navigating complex PPA structures and CO_2 offtake agreements.

3) **Engage in policy advocacy:** actively participate in the development of standards and incentives for CCU products.

4) **Drive cost reduction via modular standardization:** Shift the development mindset from "plant construction" to "product deployment." For Types B and C archetypes, the pathway to economic parity lies in "economies of numbers" rather than traditional economies

Table 1. Comparative techno-economic matrix of CO_2 utilization routes (RMB basis).

Route	TRL	Key cost drivers	Indicative LCOX (yuan/t)	Market benchmark (yuan/t)	Deployment model
e-Methanol	9	H_2 cost (electricity price), CAPEX	5,200 (e-H_2) 3,000–5,500 (COG-H_2)	~2,300 (grey)[54] ≥9,000 (green marine)[55]	B or A
Methanation	8–9	Electricity price, CAPEX	~11,500 (equiv.)	~5,000 (equiv.)[56]	B
SOEC to syngas (for MeOH)	7–8	Electricity price, stack life, CAPEX	~4,200	~2,300 (grey) ≥9,000 (green marine)	B
PtL liquid fuels (e-SAF)	7–8	Electricity price, CAPEX	20,000–28,000	~5,000 (fossil jet)[57]	B or A
Cyclic carbonates (EC)	9	Epoxide price	~3,800	~4,850[58]	A
PPC/polyols	8–9	Epoxide price, catalyst	Improves margin vs. conventional by 750–1,070	~8,300–9,500[59]	A
Electro-CO (for syngas)	6–7	Electricity price, CAPEX, stack Life	High (5.8–9.3 RMB/Nm^3)[47]	N/A (intermediate)	B
Electro-formic acid	6	Electricity price, CAPEX, stack Life	~2,500–4,000	~3,300[60]	B
MCE to solid carbon	5–6	Electricity price	21,000–29,000	60,000–300,000 (CNT powder)[61]	C or B
Thermo-aromatics	7 (pilot)	Feedstock (naphtha/MeOH), energy	Process-specific	~5,600 (benzene)[62]	A

of scale. Utilities should prioritize technology providers offering standardized, factory-built skids that minimize on-site civil works and allow for rapid, "cookie-cutter" replication across multiple power plants, thereby unlocking manufacturing learning curves.

5.4 Evolutionary portfolio: from bridging to end-state

Finally, viewed through a temporal lens, these technologies form a portfolio that evolves over time rather than a static competition. In the near term (2025–2030), routes utilizing industrial by-product hydrogen (e.g., integrated with steel or chemical complexes) serve as critical "bridging" solutions. These projects validate the CO_2 capture-and-conversion value chain and cultivate downstream markets at a lower economic entry point. As renewable electricity costs decline and electrolyzer technologies mature (2030–2045), existing synthesis infrastructure can be progressively decoupled from fossil-based by-products and retrofitted or expanded for fully electrified inputs (e.g., SOEC, Green H_2). Thus, the strategic imperative for power utilities is not to wait for the perfect "end-state" technology (like fully electrified PtL) but to deploy bridging solutions today that secure the logistical and commercial foundations for the deep decarbonization of tomorrow.

In conclusion, the catalytic utilization of CO_2 represents a transformative opportunity for the power sector to evolve from a linear emitter into a cornerstone of a circular carbon economy. By adopting a strategic, pragmatic, and boundary-aware approach, power utilities can not only meet their decarbonization obligations but also unlock new and durable revenue streams, securing their role in the energy system of the future.

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Author contribution statement

Xiansheng Li: conceptualization; methodology; Formal analysis; supervision; writing—original draft, review and editing. **Shitong Yuan**: conceptualization; investigation; data curation; visualization; writing—original draft, writing—review and editing. **Qianyu Liu**: conceptualization; methodology; formal analysis; validation; writing—original draft; writing—review and editing. **Yandong Tong**: investigation; writing—review and editing. **Pan Zhang**: investigation; writing—review and editing. **Ya Wang**: investigation; writing—review and editing. All authors read and approved the final manuscript.

Data availability

The data that support the findings of this study is available in the Electronic supplementary material.

Use of AI statement

During the preparation of this work, the authors used GPT5 and Gemini 3 in order to improve the language. After using this tool, the authors reviewed and edited the content as needed and take full responsibility for the content of the publication.

Declaration of competing interest

Xiansheng Li and Shitong Yuan are the employees of China Datang Technology Innovation Co., Ltd. All the other authors have no competing interests to declare that are relevant to the content of this article.

Electronic supplementary material

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- **Table S1:** A detailed database of international and Chinese projects for each of the ten catalytic CO_2 utilization routes discussed.
- **Table S2:** A comprehensive four-cell analysis for each route, detailing the power sector opportunity, current cost estimation, investment return, and deployment boundary conditions, complete with sources and calculations.

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