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Beyond Technological Maturity: Understanding the Institutional Trajectories of Carbon-Derived Renewable Methane in the European Energy System

Francesco Lamberti[1,2] | Pietro Ostellari[1,3] | Luciano Celi[4] | Silvia Gross[1,5] | Teresa Gatti[3] | Yifeng Zhang[6] | Daniel Fozer[6,7]

[1]Department Chemical Sciences (DISC), University of Padova, Padova, Italy | [2]Department Information Engineering (DEI), University of Padova, Padova, Italy | [3]Department Applied Science and Technology (DISAT), Polytechnic University of Torino, Torino, Italy | [4]Institute for Chemical-Physical Processes (IPCF), National Research Council, Pisa, Italy | [5]Institute for Chemical Technology and Polymer Chemistry (ITCP), Institute of Technology (KIT), Karlsruhe, Germany | [6]Department of Environmental and Resource Engineering, Technical University of Denmark, Kongens Lyngby, Denmark | [7]Centre for Absolute Sustainability, Technical University of Denmark, Kongens Lyngby, Denmark

Correspondence: Francesco Lamberti (Francesco.lamberti@unipd.it)

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ABSTRACT

Renewable methane derived from biogenic CO_2 ($bioCO_2$) occupies a paradoxical position within Europe's energy transition. $BioCO_2$-to-methane conversion is supported by a technologically credible portfolio of biological, catalytic, and hybrid routes. However, commercial maturity remains uneven across pathways, whereas institutional recognition is still ambiguous, particularly within the framework of the Renewable Energy Directive (RED III) and its provisions for Renewable Fuels of Non-Biological Origin (RFNBOs). This ambiguity cannot be explained by technological readiness alone, but it reflects the historical and conceptual foundations through which different renewable fuel families have been governed in Europe. Electricity-based pathways, such as renewable hydrogen and hydrogen-derived synthetic fuels (e-fuels), have co-evolved with regulatory frameworks that prioritize controllability, verifiable links to renewable electricity inputs, and digital traceability. These characteristics align closely with the epistemic assumptions embedded in RFNBO provisions. In contrast, renewable methane from biogenic CO_2 (hybrid bioelectrochemical methane) originates from a distinct lineage rooted in biological processes, territorially embedded infrastructures, and circular-economy practices associated with agriculture, waste management and anaerobic digestion. As a result, it remains institutionally indeterminate not because of missing rules, but because existing governance architectures privilege electricity-centric fuel pathways, leaving $bioCO_2$-derived methane only partially legible within current regulatory categories. This perspective adopts a cross-fuel conceptual approach, treating hydrogen, e-fuels, and renewable methane as institutional cases rather than technical options. Systemic readiness levels are used as an interpretative lens to situate renewable methane beyond technological maturity, highlighting the role of institutions, infrastructures, and processes of societal and institutional recognition in shaping its recognition within Europe's evolving energy system.

1 | Introduction

The role of renewable methane in Europe's energy transition is undergoing a profound re-examination[1]. Although biomethane has long been recognized as a mature component of the renewable energy landscape, the growing interest in renewable carbon-derived methane (particularly from streams of biogenic CO_2, $bioCO_2$) has exposed a deeper and largely unresolved tension within European fuel governance [1]. This debate is taking place against a backdrop of growing strategic relevance for biomethane in Europe: more than 21,000 anaerobic digestion (AD) plants are currently in operation across the continent[2], and the European Commission has set a target of 35 bcm of biomethane production by 2030 under the REPowerEU framework[3]. Technologies capable of converting bioCO_2 into CH_4 have progressed steadily over the past two decades, forming a diversified portfolio of biological, catalytic, and hybrid routes. However, these pathways do not share the same degree of commercial maturity, and their current levels of market uptake remain uneven across Europe [2–4]. For clarity, this perspective uses renewable methane as an umbrella term encompassing methane produced from renewable or biogenic carbon sources through biological, catalytic, and hybrid conversion pathways. Within this category, biomethane refers to methane generated through AD and related biological upgrading processes, whereas e-methane denotes synthetic methane produced through power-to-methane routes using renewable hydrogen and is considered a specific subset of the broader e-fuel family; renewable methane derived from biogenic CO_2 or bioCO_2-derived methane refers to hybrid bioelectrochemical methane technologies. From a technical perspective, bioCO_2-to-CH_4 conversion involves the reduction of CO_2 and can proceed through different electron-supply pathways. Electrons may be provided indirectly through hydrogen, generated by biological or electrochemical processes [5], or transferred directly to methanogenic microorganisms through bioelectrochemical interfaces [6]. In the latter case, the development of suitable cathodes [7] or photocathodes, such as Cu_2O-based systems [8, 9], becomes critical for enabling efficient electron delivery, as described elsewhere in the specialized literature [10]. Despite these technological advances, the institutional status of bioCO_2-derived methane remains unsettled. Its position within the current legislative and certification architecture, particularly in relation to the RED III framework and its criteria for Renewable Fuels of Non-Biological Origin (RFNBOs), remains ambiguous[4]. This ambiguity reflects deeper structural dynamics within European fuel governance. Rather than resulting from a simple regulatory omission, it emerges from the historical layering of policy instruments, certification logics, and socio-technical expectations that have evolved around different renewable fuel families.

Electrolysis-based pathways, such as renewable hydrogen [11, 12] and e-fuels [13, 14], have shaped the conceptual core of European RFNBO provisions; their characteristics, for example production controllability, electricity correlation, and digital traceability, align naturally with the interpretative categories embedded in RED III. This asymmetry should not be read as a regulatory oversight but as the outcome of historically contingent coevolution between specific fuel technologies and the governance instruments developed to support them.

In contrast, renewable methane from bioCO_2 emerges from biological processes and locally anchored resource systems that do not neatly map onto the same regulatory abstractions[5]. Although the degree of commercial maturity remains uneven across biological, catalytic, and power-to-methane pathways, the question is not only whether these technologies are ready to scale but also whether the institutional frameworks designed around other fuels can effectively accommodate them. The argument developed in this perspective is therefore not that public ambiguity is the sole constraint on scale-up, but that it disproportionately affects pathways that are technically credible, infrastructure-compatible, and increasingly relevant for European energy system integration. To avoid treating renewable methane as a homogeneous category, Figure 1 distinguishes the main pathway families considered in this article, namely AD-based biomethane, catalytic e-methane, and hybrid bioelectrochemical methane, and relates each of them to its indicative TRL and governance position within the European renewable fuel landscape. This configuration is best understood from a system-level perspective. The position of bioCO_2-derived methane in the European energy system is shaped not only by technologies and infrastructures but also by the interpretative frameworks through which institutions classify fuels, the public narratives that influence legitimacy, and the historically contingent architectures of certification and registry schemes. Rather than proposing solutions or interventions, this perspective article examines how these heterogeneous dimensions have

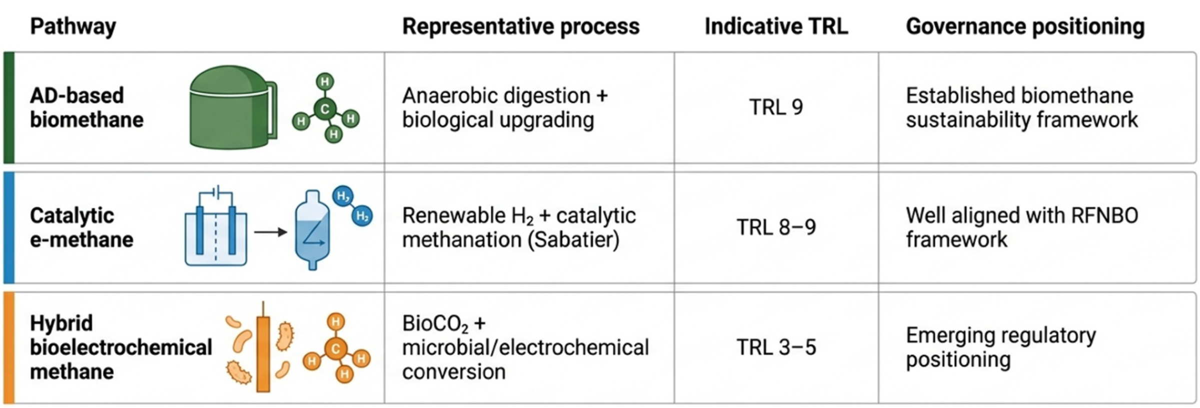

FIGURE 1 | Representative renewable methane pathways, their characteristic conversion processes, indicative technology readiness levels (TRLs), and governance positioning within the European fuel landscape. The figure distinguishes established AD-based biomethane systems, catalytic e-methane routes, and emerging hybrid bioelectrochemical methane pathways.

produced a category that is technologically diverse yet institutionally indeterminate. By articulating the conceptual, institutional, and socio-technical dynamics that shape this indeterminacy, we aim to contribute to a broader scholarly conversation on fuel recognition, regulatory evolution, and the future trajectories of renewable methane in Europe.

2 | Technological Maturity and the Overlooked Systemic Dimension

The technological foundations of renewable methane production are substantially more consolidated than its current institutional positioning might suggest. Across Europe and beyond, biological, catalytic, and hybrid methanation pathways benefit from decades of technical and scientific development, producing a diverse and highly resilient technological landscape. Biological routes, including anaerobic digestion and microbial CO_2 reduction [15, 16], form one of the most established renewable-fuel system, with related infrastructures, in operation today. They draw on widely distributed and abundant biomass resources, rely on mature reactor designs, and benefit from well-understood process control and optimisation strategies. Taken together, these biological infrastructures, from the nearly 21,300 decentralized anaerobic-digestion plants operating across Europe to the industrial-scale microbial CO_2-to-CH_4 reactors now integrated in Denmark, Switzerland and the United States[6], constitute one of the most extensive and territorially rooted renewable-fuel production systems currently in operation. Their extensive deployment, operational stability, and long operational history reinforce the central point of this perspective: technological maturity in the renewable-methane domain is already well established, even if institutional recognition has not evolved at the same pace. In parallel, catalytic methanation, most prominently the Sabatier reaction [17], has reached a level of reproducibility and robustness that enables scale-up in industrial settings, often coupled with renewable hydrogen sources [18, 19]. Hybrid configurations that integrate biotic and abiotic mechanisms, such as bio-electrochemical systems or intensified biocatalytic reactors [20], have further expanded the portfolio by merging the operational stability of catalytic processes with the selectivity and adaptive properties of biological pathways [21].

Taken together, these technologies form a continuum rather than separate silos. They differ in kinetics, operational envelopes, carbon-source nature, availability and flexibility, and process configuration, but converge on the same functional outcome: transforming renewable or biogenic carbon streams into methane that can, when compliant with gas-quality requirements, be integrated into already existing gas infrastructures. Importantly, the renewable methane landscape should not be treated as technologically homogeneous. Biological upgrading routes linked to anaerobic digestion and biomethane infrastructures are comparatively well established, whereas power-to-methane configurations based on externally supplied renewable hydrogen remain less commercially deployed, with only a limited number of commercial-scale e-methane facilities currently operating in Europe[7]. Catalytic methanation, including Sabatier-based routes, provides a mature chemical foundation, but its integration into full renewable-fuel value chains depends on process configuration, hydrogen sourcing, and compliance with the system-level requirements established for RFNBOs, including additionality, temporal correlation, geographical correlation, and greenhouse-gas accounting under the relevant Delegated Acts[8].

However, technical viability alone does not ensure institutional recognition, shifting the challenge from technological optimization to institutional positioning[9]. The European regulatory architecture has evolved along trajectories shaped by macro-trends, most notably the rise of electrolysis-based hydrogen and synthetic fuels, which have profoundly influenced how "future fuels" are conceptually framed. This lineage has embedded a series of expectations into policy design that privilege controllability, electricity correlation, auditable accounting, and digital traceability, all of which mirror the characteristics of hydrogen and e-fuel pathways. In contrast, biological and hybrid methanation routes emerged within a different classification and infrastructural paradigm, shaped by decentralized territorially based systems rather than electricity-centric ones. These divergent lineages produce a structural friction. What is technologically coherent and widely adopted can appear, from a regulatory vantage point, heterogeneous or difficult to categorize. In this sense, renewable methane instead reflects a misalignment between established technologies and prevailing regulatory frameworks. This mismatch is reinforced by historical lock-ins: regulatory instruments were developed to accelerate the integration of electrolysis-based fuels, and the categories, metrics, and compliance logic that emerged from that process now serve as default abstractions for new fuels entering the policy landscape[10].

Mature technologies encounter governance frameworks that were not designed with their characteristics in mind, leaving readiness high but visibility, classification, and alignment incomplete. Recognizing this broader dimension is essential to understanding renewable methane's uncertain place in Europe's evolving energy landscape and fuel governance, and why greater conceptual clarity is needed alongside technological progress.

3 | A Cross-Fuel Conceptual Perspective on RFNBO Recognition

RFNBO recognition in Europe emerges from the interaction of multiple fuel trajectories rather than from isolated pathways. Rather, it reflects the differentiated historical, epistemic and institutional trajectories through which distinct renewable fuel families have emerged, stabilized, and been integrated into European energy governance. Hydrogen [22], e-fuels, and renewable methane derived from carbon sources [23] have not simply followed different technological development paths; they have co-evolved with specific policy instruments, certification logics and imaginaries of what constitutes a "future-proof" renewable fuel [24, 25]. These co-evolutionary processes have shaped how each fuel is conceptualized, rendered legible to institutions, and ultimately recognized under frameworks such as RED III.

Renewable hydrogen occupies a singular position within this landscape. Its rise has been closely intertwined with the expansion of electricity-centric decarbonization strategies, digital energy systems, and market-based coordination mechanisms. As a result, hydrogen governance has developed around classification regime that privileges measurable production pathways, modular system architectures, and traceable energy inputs. Concepts such as additionality, requiring renewable fuels to be linked to new renewable electricity generation, temporal and geographical correlation[11], and granular accounting of renewable electricity inputs emerged alongside the maturation of electrolysis technologies and the increasing availability of time-resolved data on renewable electricity generation, grid conditions, and fuel production. Within this regime, fuels are conceptualized as outputs of tightly coupled electricity-to-molecule conversion processes, whose compliance can be demonstrated through standardized metrics and digital certification architectures[12].

E-fuels [26], including synthetic hydrocarbons and alcohols produced through hydrogen-based pathways, inherit much of how fuels are categorized across regulatory frameworks. Although chemically diverse, they are institutionally anchored in the same conceptual universe as "renewable hydrogen". Their recognition as RFNBOs is largely determined by the renewable-hydrogen input used in their production. As a result, governance frameworks assess compliance primarily through hydrogen-related criteria, which are subsequently extended to downstream molecules. In biological methane pathways, in contrast, hydrogen may act as a metabolic intermediate, but it is not the basis upon which the fuel is classified or certified. This inheritance reinforces a model in which renewable fuels are understood primarily as extensions of power-to-X systems, governed through electricity correlation, centralized accounting frameworks, and relatively uniform certification logics. In this sense, e-fuels do not constitute a distinct category but rather a derivative institutional case shaped by hydrogen-centric assumptions.

Renewable methane[13] derived from carbon sources, and in particular from biogenic CO_2, follows a markedly different institutional trajectory [27]. Its development predates the rise of RFNBO discourse and emerges from biologically mediated place-based systems. These origins have given rise to an epistemic regime in which fuels are conceptualized through material cycles, local resource integration, and long-term system resilience rather than through real-time controllability or electricity coupling. Although this perspective focuses on renewable methane as a paradigmatic case, similar externalities, and dynamics may also characterize other renewable fuels derived from biogenic CO_2 through biological conversion pathways. Certification practices for biomethane evolved accordingly, focusing on feedstock sustainability[14], greenhouse-gas emissions reduction, and associated traceability/documentation frameworks. These logics differ fundamentally from those that underpin RFNBO governance, even when the resulting molecule, methane, is chemically identical to synthetic alternatives.

From this cross-fuel perspective, the position of renewable methane derived from biogenic carbon within RED III does not reflect a lack of maturity or legitimacy, but a divergence in conceptual foundations. RED III does not merely regulate fuels; it operationalizes a particular way of seeing them. The criteria embedded in RFNBO provisions implicitly privilege fuel pathways that align with electricity-based classification regimes, whereas pathways emerging from biological and territorial systems appear less readily legible within the same framework. This divergence is not the result of inconsistency or omission, but of the historical sequencing [28] through which different fuel families entered in the European policy debates and governance structures [29].

TABLE 1 | Conceptual comparison of renewable fuel families as institutional cases.

Dimension	Renewable hydrogen	e-fuels (including e-methane)	Renewable methane from bioCO_2 (hybrid bioelectrochemical methane)
Dominant epistemic regime	Electricity-centric conversion; real-time controllability and modularity	Derivative of the hydrogen-centric epistemic regime	Biological and carbon-cycle-based regime; territorially embedded processes
Primary governance logic	Power-to-X pathways governed through electricity correlation and additionality	Hydrogen-mediated governance extending RFNBO criteria to downstream molecules	Feedstock sustainability and circular-economy logics rooted in biogenic carbon flows
Certification & accounting archetype	Digitally mediated certification based on granular, time- and location-correlated electricity inputs	Compliance-centered accounting anchored to renewable hydrogen compliance	Sustainability verification linked to biomethane frameworks and registry-based traceability
Infrastructure & system embedding	Emerging infrastructures enabling sector coupling and flexible energy conversion	Power-to-X chains linked to existing end-use sectors and emerging synthetic-fuel supply systems	Often embedded in existing gas infrastructures and biomethane-related value chains, with relevance for storage and seasonal system resilience
Institutional anchoring (indicative)	~2018–2023 (EU hydrogen strategy, RFNBO delegated acts)	~2020–2023 (PtX extension within RFNBO framework)	No dedicated legal category; currently interfacing with existing biomethane sustainability frameworks (RED article 29)

Note: Indicative timeframes refer to periods of institutional consolidation within EU energy governance, not to technological maturity or performance.

Table 1 schematically illustrates this differentiation by comparing hydrogen, e-fuels and renewable methane from bioCO_2 as institutional cases rather than technical options. The matrix does not assess performance or compliance; instead, it highlights how each fuel family has come to be associated with distinct governance expectations, certification architectures, and interpretative categories. By foregrounding these differences, the comparison underscores that RFNBO recognition is shaped as much by institutional genealogy as by technological characteristics.

Adopting a cross-fuel conceptual perspective thus allows renewable methane from bioCO_2 (hybrid bioelectrochemical methane) to be situated not as an outlier or exception, but as a pathway governed by a different epistemic lineage. Understanding this distinction is essential for analyzing why carbon-derived methane pathways, despite differing levels of technological maturity, occupy an ambiguous position within current RFNBO frameworks, and why debates around its recognition cannot be reduced to questions of technical alignment alone. Instead, they reflect deeper issues of how renewable fuels are categorized, normalized and rendered governable within Europe's evolving energy system.

4 | Certification Logics and Europe's Heterogeneous Institutional Architecture

The certification of renewable gases in Europe has not emerged from a single harmonized design but from a layered historically contingent process shaped by national energy systems, regulatory traditions, and market structures. Member States (MSs) developed certification and registry architectures in response to different policy priorities, infrastructural configurations, and sectoral histories, long before the introduction of RFNBOs as a distinct regulatory category[15]. As a result, Europe today hosts a heterogeneous institutional landscape in which multiple certification and implementation context coexist [30], each reflecting the specific pathways through which renewable gases were integrated into national energy systems [27].

In many MSs, biomethane certification evolved within pre-existing agricultural, waste-management and renewable-energy support frameworks. Guarantees of origin and registry systems supported traceability and market use, whereas sustainability verification and mass-balance procedures were used to demonstrate compliance with RED-related sustainability requirements. These systems prioritized feedstock sustainability, greenhouse gas emissions, lifecycle climate change impacts, and traceability through registries rather than real-time correlation with electricity production. Over time, such approaches became institutionalized within national regulatory agencies, transmission system operators, and registry platforms, producing stable yet diverse certification practices across Europe[16].

In contrast, the governance of renewable hydrogen and RFNBO pathways entered European policy debates through a different institutional channel, closely aligned with electricity market design, industrial decarbonization strategies, and policy instruments supporting the scale-up of renewable hydrogen. Certification logics in this domain were shaped by the need to demonstrate renewable electricity sourcing[17], additionality and temporal alignment, leading to architectures that emphasize granular data reporting, digital verification and cross-sectoral coordination[18]. When these logics were later codified at EU level, particularly through RED III and its delegated acts, they reflected the epistemic assumptions and governance expectations associated with electricity-based fuels.

The coexistence of these certification regimes reflects interpretative asymmetries rooted in Europe's multilevel governance structure. Different fuel pathways entered the policy arena at different moments, through different institutional gateways, and were stabilized under distinct regulatory rationales. National certification systems thus encode historical choices about what aspects of renewable fuels matter most, for example, origin of carbon, mode of production, system integration, or temporal controllability, without necessarily converging on a single interpretative framework.

Within this context, renewable methane derived from biogenic CO_2 occupies a distinctive position. It is neither a novel fuel awaiting regulatory attention nor a fully settled category within the RFNBO framework. Instead, it can be understood as a category in search of conceptual anchoring at the EU level. Its certification draws on well-established biomethane logics centered on feedstock sustainability, greenhouse-gas emissions reduction, and integration within existing registry frameworks, while simultaneously intersecting with emerging RFNBO concepts developed around different fuel genealogies. Registries primarily issue and manage Guarantees of Origin (GO), which may be linked to certified or noncertified biomethane, whereas sustainability certification is associated with EU-recognised voluntary schemes or national certification systems. Although the underlying principles of sustainability certification and registry-based traceability are rooted in RED III, their implementation remains uneven across Europe. In particular, the tradability of certificates across registries varies among Member States, partly because registries may be connected to different cross-border transfer hubs, such as AIB or ERGaR[19], and not all European countries currently operate a functioning biomethane registry. This creates practical limits to cross-border integration and mutual recognition of GOs, thereby constraining the development of a fully integrated European biomethane market.

Understanding this plurality is essential for contextualizing current debates on RFNBO recognition. The challenge is therefore not simply the absence of regulation, but the coexistence of sustainability certification, registry-based traceability, and national implementation practices that are only partially aligned across Member States. For CO_2-derived renewable methane, this institutional layering reinforces the difficulty of positioning the pathway within RFNBO frameworks originally developed around electricity-based fuel genealogies.

5 | Actors, Infrastructures and the Complexity of Institutional Interfaces

The position of renewable methane derived from biogenic CO_2 within the European energy system cannot be understood solely through regulatory categories or certification logics. It is equally shaped by the dense network of actors, infrastructures, technologies, and institutional interfaces through which biomethane is produced, transported, certified, and valorized. These interfaces connect sectors that have evolved according to different temporalities, governance traditions and infrastructural logics, giving rise to a form of interface complexity that goes beyond conventional notions of regulatory or technical barriers.

At the production end, biomethane is rooted in biological and locally anchored systems, all governed by sector-specific policies, local authorities, and long-established operational routines. Across Europe, farmers, waste operators and municipal utilities (such as those involved in agricultural biomethane production by companies such as Nature Energy or BTS Biogas, and in waste-based biomethane pathways operated by SUEZ and Veolia) interact with regulatory frameworks originally designed for nutrient management, waste treatment, and rural development rather than for fuel markets. These actors operate within territorially anchored systems characterized by long investment cycles and strong place-based dependencies, which shape how biomethane projects are conceived and managed.

Downstream, renewable methane interfaces with gas infrastructures that were historically developed for fossil natural gas. Although methane-based fuels are generally compatible with existing gas networks, grid injection still depends on compliance with gas-quality specifications, including methane concentration, impurity levels, moisture content and other parameters relevant to network safety and interoperability. Transmission and distribution system operators (such as SNAM, GRTgaz, Gasunie and Open Grid Europe, operating within the coordination framework of ENTSOG) constitute a layer of institutional actors whose mandates prioritize system reliability, safety and cost efficiency. The integration of biomethane into these legacy infrastructures has generally been successful from a technical perspective, provided that gas-quality specifications for grid injection are met. However, this technical compatibility does not remove the need for governance arrangements that can attribute renewable origin, sustainability characteristics, and production pathway information to an otherwise indistinguishable methane molecule. These expectations reflect institutional inertia embedded in infrastructures that were designed to transport gas according to quality and safety parameters, not to differentiate molecules on the basis of production pathways.

A further layer of complexity emerges at the interfaces among energy, climate, and sustainability governance. Certification bodies, registry operators, national regulators, and EU-level institutions interact to translate sustainability criteria, greenhouse-gas accounting rules, and market eligibility requirements into operational practices. These actors often operate across multiple policy domains, each with its own logic and timing. As a result, the institutional interfaces governing renewable methane are shaped by asynchronous developments: sustainability criteria may evolve at a different pace than gas market rules, while emerging policy categories such as RFNBOs may require new processes of interpretation and operationalization within existing certification and registry frameworks.

Crucially, these interface dynamics should not be interpreted as obstacles or failures. Rather, they reflect the layered accumulation of institutional arrangements developed to address different policy objectives over time. Legacy infrastructures and established actor constellations not only introduce forms of institutional inertia that stabilize existing practices but they also provide the foundation upon which renewable methane has been able to scale and integrate into the energy system[20]. The challenge lies not in removing these interfaces, but in understanding how their historical sequencing and sectoral differentiation shape the current positioning of biomethane within European fuel governance. The implications of this institutional layering become particularly visible in the case of emerging hybrid bioelectrochemical methane pathways. Unlike conventional biomethane, which is clearly anchored within existing sustainability frameworks, or e-methane, which can be assessed through RFNBO provisions, hybrid pathways currently lack a dedicated legal category. As a result, they may be interpreted through existing biomethane frameworks despite relying on process logics that differ substantially from conventional AD and upgrading routes. This ambiguity extends beyond certification and traceability. It may also influence access to policy instruments, support mechanisms, and investment frameworks that are often structured around legally recognized fuel categories. Consequently, institutional uncertainty may persist even where the underlying technology demonstrates technical feasibility and environmental performance. Similar dynamics have previously accompanied the emergence of renewable hydrogen[21], recycled carbon fuels[22], hydrogen certification systems[23], and even biomethane itself[24], where technological development often preceded the establishment of dedicated regulatory categories and governance arrangements. In such cases, institutional recognition evolved only gradually as governance frameworks adapted to technologies that did not fit existing classifications.

Taken together, these dynamics reveal that the institutional positioning of renewable methane is shaped as much by historical governance trajectories as by technological capabilities. Renewable methane does not enter an institutional vacuum; rather, it encounters a landscape populated by established actors, infrastructures, certification systems, and policy frameworks that were developed around different fuel categories and policy objectives. Understanding how these interfaces interact is therefore essential for explaining why some pathways achieve rapid institutional recognition while others remain conceptually and regulatory indeterminate despite increasing technological maturity.

6 | Public Narratives, Perception Dynamics, and Societal Legitimacy

The societal legitimacy of renewable methane derived from bioCO_2 cannot be inferred solely from its technological maturity; it is shaped by public imaginaries, historical associations, and evolving expectations surrounding the energy transition. Social science research has consistently shown that energy technologies are interpreted through narratives, symbols, and place-based meanings rather than solely through performance metrics [31, 32]. Unlike electrification, supported by highly visible technologies such as rooftop photovoltaic systems or electric vehicles, renewable methane from bioCO_2 lacks a distinct visual or experiential identity and remains largely invisible to end users. As a molecule physically indistinguishable from fossil natural gas, it often inherits the negative connotations associated with the latter, reinforcing skepticism and shifting the basis of trust away from direct experience toward institutional certification and regulatory mediation [33].

Beyond legal classification and certification, the long-term integration of renewable methane also depends on processes of institutional and societal legitimization [34]. Because renewable methane cannot be distinguished at the point of use, its legitimacy depends less on direct sensory or place-based engagement and more on trust in certification systems, guarantees of origin, and public authorities. In this respect, legitimacy is not only socially constructed but also institutionally mediated, making trust in governance frameworks central to public acceptance.

Here, the focus is on societal legitimacy rather than on the local acceptability of individual biomethane plants. Where such trust is fragile or contested, renewable methane may be perceived less as a distinct low-carbon pathway and more as a continuation of existing gas-based systems. This symbolic association is only one dimension of societal legitimacy and should be distinguished from the local acceptance of specific plants or infrastructures, which is shaped by additional factors such as participation and public engagement initiatives, plant size, logistics, odor, place-based concerns, and distributive justice [35–38]. More broadly, societal responses to renewable energy pathways are also shaped by socio-economic conditions, generational effects, information and communication dynamics, and wider energy-policy attitudes [39, 40]. Similar multi-factor patterns have also been documented in the broader literature on hydrogen acceptance [41].

A further source of misunderstanding arises from the limited visibility within public narratives, of renewable methane's contribution to seasonal energy storage and system resilience. Public debates on the energy transition tend to emphasize instantaneous efficiency, short-term storage, and direct electrification, whereas the need for long-term, molecule-based energy storage remains largely outside mainstream awareness. Similar dynamics have been observed in public discourses on hydrogen and other multi-sector transition technologies, where simplified narratives obscure system-level constraints and trade-offs [22]. Within this cognitive frame, the conversion of bioCO_2 into methane is frequently interpreted not as a structural requirement for balancing seasonal variability and ensuring system resilience but as a continuity mechanism for the gas industry. This interpretation reveals a persistent misalignment between the operational realities of integrated energy systems and the expectations shaped by dominant public narratives.

In addition, the societal legitimacy of renewable methane depends on a broader reframing of how CO_2 itself is conceptualized [42]. Environmental narratives in Europe have traditionally portrayed CO_2 primarily as a waste stream to be eliminated. Research studies on carbon capture, utilization, and storage shows that public acceptance hinges on whether CO_2 is framed as a pollutant to be buried or as a circular feedstock with a defined and transparent origin [42, 43]. The emergence of carbon capture and utilization pathways challenges conventional "decarbonization" narratives by requiring a shift toward "defossilization", in which the origin of carbon, biogenic versus fossil, becomes central to claims of sustainability and legitimacy [44]. Such cognitive and narrative shifts cannot rely solely on technical communication. They require participatory engagement, transparency, and credible institutional mediation to build trust and societal legitimacy. Without this reframing, renewable methane risks remaining symbolically anchored to its fossil lineage, undermining its potential recognition as a strategic component of carbon circularity, seasonal resilience, and long-term European energy security. Although legal recognition ultimately determines access to certification frameworks, incentives, and market mechanisms, societal legitimacy influences the broader acceptance of these arrangements and their capacity to support long-term deployment.

7 | Beyond TRL: Situating Renewable Methane in a Systemic Readiness Perspective

The discussion surrounding renewable methane derived from biogenic CO_2 has often been implicitly framed in terms of technological readiness. However, as the preceding sections have shown, the challenges and ambiguities surrounding its position within European fuel governance cannot be understood through technology-focused metrics alone. In this context, the concept of systemic readiness levels (SRL) offers a useful interpretative lens, not as an assessment or ranking tool but as a conceptual lens to articulate how technologies interact with the institutional, infrastructural, and societal systems in which they are embedded. [45]. Unlike technological readiness level (TRL), which focuses on the internal development status of a technology, SRL foregrounds the co-evolution between technical artefacts and the systems that enable, constrain or shape their adoption. Applied conceptually, SRL shifts attention from whether a technology "works" to whether the surrounding system is prepared to recognize, govern and integrate it. For renewable methane, this distinction is particularly salient: technological pathways for converting bioCO_2 into methane are well established, yet their institutional positioning remains indeterminate because readiness is distributed across multiple, interdependent dimensions.

From this perspective, readiness emerges at the intersection of certification, institutions, infrastructures, and societal narratives [46]. Certification systems determine how fuels are classified, traced, and legitimized within markets; institutional arrangements shape how rules are interpreted and implemented across MSs; infrastructures embed historical expectations and operational constraints; and public narratives affect the legitimacy of fuels that remain largely invisible to end users. These dimensions cannot be reduced to a single metric or maturity scale, yet together they shape whether a fuel pathway is perceived as compatible with existing governance frameworks.

Importantly, this perspective does not imply deficiency or delay [47]. These differences reflect the historical sequencing through which renewable methane entered European energy systems. In this sense, renewable methane is not "lagging" behind other fuels, but is embedded in a different configuration, shaped by gas infrastructures and territorially anchored resource systems rather than electricity-centric conversion chains. Used as a conceptual framework, SRL helps make this distinction visible without turning it into a normative judgment [48].

Situating renewable methane within a systemic readiness perspective allows its current status to be understood as the result of partial alignment between technically credible pathways and governance structures shaped by other fuel trajectories. This shifts the debate beyond optimization or compliance toward a broader understanding of readiness across socio-technical systems. In this sense, SRL serves not as an evaluative tool, but as a heuristic one, linking the technological, institutional, and societal dimensions discussed in this article.

8 | Possible Long-Term Trajectories for Renewable Methane Recognition (2025–2035)

Rather than following a linear roadmap, the future positioning of renewable methane derived from biogenic CO_2 within the European energy system is more plausibly understood through a set of possible trajectories shaped by the coevolution of institutions, infrastructures, and societal narratives (Figure 2). These trajectories do not prescribe policy or outline desired outcomes but rather reflect different ways in which existing dynamics could stabilize, reconfigure, or gradually realign over time. Their purpose is not to anticipate regulatory decisions but to illustrate how recognition may evolve as systemic readiness changes across multiple dimensions.

One possible trajectory is characterized by incremental institutional accommodation [49]. In this configuration, renewable methane from bioCO_2 continues to be governed primarily by existing biomethane certification logics, while selectively interfacing with RFNBO-related concepts where technical or administrative overlaps emerge. Institutional recognition evolves through pragmatic interpretation rather than formal reclassification, allowing renewable methane from bioCO_2 to remain embedded in gas infrastructures and circular-economy frameworks. This trajectory preserves continuity with established practices and actors while maintaining a degree of conceptual ambiguity, as renewable methane from bioCO_2 remains legible across multiple overlapping governance frames.

A second configuration centers on narrative and conceptual reframing [50]. Here, renewable methane from bioCO_2 gradually shifts from being perceived as a "cleaner substitute" for fossil natural gas, a framing that often triggers concerns about prolonging dependence on gas infrastructures, to being understood as a form of chemical renewable energy storage. In this interpretation, its value lies less in fuel substitution and more in its role within a resilient seasonally balanced energy system. Such a reframing aligns renewable methane from bioCO_2 more closely with electrification narratives by positioning it as a complementary storage vector rather than a competing pathway. Institutional recognition in this trajectory is driven less by regulatory redesign than by changes in how the molecule is situated within broader energy imaginaries.

A third pathway emphasizes increased visibility of carbon circularity through evolving certification and transparency practices [51]. As renewable methane from bioCO_2 remains physically indistinguishable from its fossil counterpart, legitimacy increasingly depends on the ability of institutions to make process attributes visible and intelligible. In this trajectory, recognition is shaped by the growing prominence of digital registries, guarantees of origin, and lifecycle-based information that enable societal actors to engage with the origin and transformation of carbon, rather than with the molecule alone. Importantly, this does not imply a uniform or fully harmonized system, but rather a gradual strengthening of narrative coherence across heterogeneous certification architectures.

Across all trajectories, a common feature is the absence of sharp transitions or definitive endpoints. Institutional change unfolds through reinterpretation, layering, and partial alignment rather than replacement. Renewable methane from bioCO_2 does not

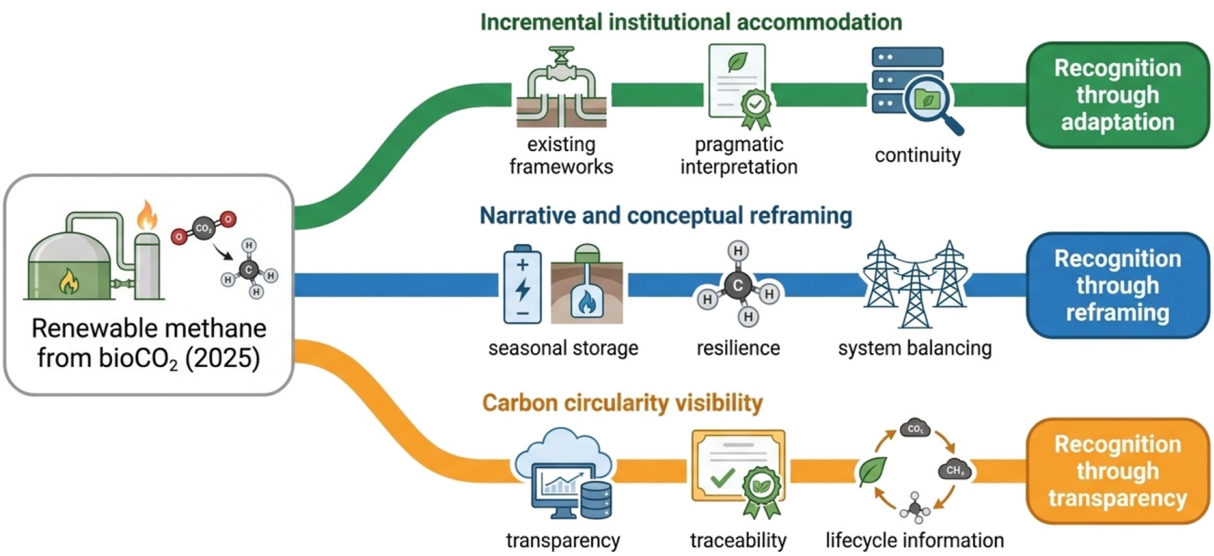

FIGURE 2 | Conceptual representation of possible long-term trajectories for renewable methane recognition in Europe (2025–2035). The pathways illustrate how institutional accommodation, narrative reframing, and enhanced visibility of carbon circularity may contribute, individually or in combination, to the progressive recognition of renewable methane within evolving energy governance frameworks. The trajectories are illustrative rather than predictive and may coexist across Member States and sectors.

"arrive" at recognition through a single regulatory act, but through the gradual convergence of institutional expectations, infrastructural practices, and societal meaning-making. In this sense, divergent trajectories may coexist across MSs and sectors, reflecting Europe's heterogeneous energy landscape.

Taken together, these reflections underscore the central contribution of this perspective. The challenges surrounding renewable methane from bioCO_2 emerge from the interaction between technologically diverse pathways and governance frameworks shaped by different fuel genealogies. By adopting a systemic lens, rather than an operational or deficit-based approach, this article contributes to a broader understanding of how fuel recognition emerges at the intersection of institutions, infrastructures and narratives. In doing so, it offers a conceptual framework for interpreting the evolving role of renewable methane within Europe's energy transition, while also identifying possible directions through which policymakers, regulators, and institutions may better align legal definitions, certification architectures, and system-level recognition with emerging renewable methane pathways.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data sharing not applicable to this article as no datasets were generated or analysed during the current study.

Endnotes

[1] See REPower EU Roadmap of 2025 and to Post-2030 Renewable energy framework – Public consultation—European Commission of 2026.

[2] European Biogas Association (EBA) Statistical Report 2025, Brussels, Belgium, December 2025.

[3] European Commission. *REPowerEU Plan*. COM (2022) 230 final, Brussels, 2022.

[4] RED III (Directive (EU) 2023/2413) defines RFNBO eligibility primarily through hydrogen-focused Delegated Acts (EU) 2023/1184 and 2023/1185, which clarify additionality, temporal and geographical correlation, and traceability requirements. However, no equivalent delegated provisions explicitly address CO_2-to-methane pathways, leaving bioCO_2-derived methane without a harmonised route to RFNBO certification.

[5] See IEA, "Outlook for Biogas and Biomethane" (2020), which emphasises that biomethane supply chains are inherently decentralised, geographically dispersed and rooted in locally available biological feedstocks.

[6] https://www.electrochaea.com, reporting commercial-scale microbial CO_2-to-CH_4 deployments.

[7] EBA Report 2024, "Mapping e-methane plants and technologies", Brussels, September 2024. The report claims that in 2024 there were only seven e-methane facilities in a commercial scale level in Europe.

[8] Commission Delegated Regulation (EU) 2023/1184 of 10 February 2023 supplementing Directive (EU) 2018/2001 by establishing a Union methodology setting out detailed rules for the production of renewable liquid and gaseous transport fuels of non-biological origin. Official Journal of the European Union, L 157, 20.6.2023, 11–19; Commission Delegated Regulation (EU) 2023/1185 of 10 February 2023 supplementing Directive (EU) 2018/2001 by establishing a minimum threshold for greenhouse gas emissions savings of recycled carbon fuels and by specifying a methodology for assessing greenhouse gas emissions savings from renewable liquid and gaseous transport fuels of non-biological origin and from recycled carbon fuels. Official Journal of the European Union, L 157, 20.6.2023, 20–33.

[9] European Court of Auditors (ECA), Special Report 05/2018, "Renewable energy for sustainable rural development: significant potential synergies, but mostly unrealised". The report highlights that technological maturity in renewable-energy solutions does not necessarily translate into institutional recognition or effective deployment, due to regulatory fragmentation, administrative barriers, and inconsistent policy support.

[10] EC, Commission Staff Working Document SWD (2021) 621 final. The document highlights how the regulatory architecture for renewable fuels was fundamentally shaped around electrolysis-based hydrogen, creating path-dependencies in categories, metrics, and compliance logic that now act as default frameworks for new renewable-fuel pathways.

[11] which have been operationalised in RED III primarily through the delegated acts on renewable hydrogen (European Commission, 2023). See also European Commission (2020), A hydrogen strategy for a climate-neutral Europe. COM(2020) 301 final.

[12] For example, CertifHy (2019). CertifHy – Design of a European renewable hydrogen certification scheme. See: https://www.certifhy.eu.

[13] See IEA (2020). Outlook for biogas and biomethane: Prospects for organic growth.

[14] See European Commission, 2018; BIP Task Force 3.4, 2024.

[15] See Council of European Energy Regulators (CEER) (2018), Status Review of Guarantees of Origin across Europe.

[16] See S&P Global (October 2024) Renewable gas tracking systems – Value of biomethane/RNG certificates. https://www.europeanbiogas.eu/wp-content/uploads/2025/06/Value-of-Biomethane-Certficates-Study-Complete-White-Paper-FINAL-for-Publishing-20241021.pdf.

[17] See https://www.euractiv.com/news/leak-long-awaited-eu-rules-on-renewable-hydrogen-expected-15-dec/.

[18] See Agora Energiewende and Guidehouse (2021): Making renewable hydrogen cost-competitive: Policy instruments for supporting green H_2.

[19] Association of Issuing Bodies (AIB, https://www.aib-net.org/eecs) and European Renewable Gas Registry (ERGaR) is the association dedicated to enabling cross-border trade of renewable gas certificates across Europe (https://www.ergar.org).

[20] See https://pr.euractiv.com/pr/gas-package-grants-better-access-renewable-gas-eu-market-225872.

[21] The regulatory definition and certification architecture for renewable hydrogen evolved progressively through the development of the RFNBO framework under RED II and subsequent Delegated

Regulations (EU) 2023/1184 and 2023/1185, several years after large-scale electrolysis projects had begun to emerge.

[22] Recycled Carbon Fuels (RCFs) are a regulatory category covering fuels derived from unavoidable non-renewable waste and process gases. They occupied an intermediate position between fossil and renewable fuel categories before receiving dedicated treatment within the RED framework and associated implementing provisions.

[23] Early hydrogen deployment preceded the establishment of harmonised certification and Guarantees of Origin systems, which were subsequently developed through initiatives such as CertifHy and evolving EU hydrogen market regulations.

[24] Biomethane technologies became commercially established before the emergence of the current European architecture of sustainability certification, Guarantees of Origin, and cross-border registry systems.

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