Pathways for Promoting Modern Agricultural Development through biomethane Project: A Comparative Study of China and Serbia

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Abstract:

The biomethane industry has been traditionally constrained by energy-oriented development models characterized by low profitability and strong dependence on policy support. In recent years, integrated development with modern agriculture has emerged as a promising pathway to overcome these limitations.

This study develops a four-dimensional analytical framework based on circular agriculture theory, industrial ecosystem theory, and value chain theory, focusing on: (i) feedstock collection and organizational models, (ii) technology pathways and product application, (iii) value realization and business models, and (iv) institutional support. Using a comparative case study approach, the paper analyzes representative experiences from China and evaluates their relevance for Serbia.

The results indicate that the economic sustainability of biomethane systems depends on the integration of upstream waste management and downstream agricultural value-added services, rather than on energy production alone. Stable feedstock supply, diversified revenue streams, and coordinated policy support across the value chain are identified as key enabling factors.

Based on Serbia's current biogas sector, agricultural structure, and resource base, the study proposes a phased development pathway, including the strengthening of feedstock aggregation systems, the development of diversified business models, and the gradual integration of biomethane into the energy system.

Keywords:

Biomethane; Modern Agriculture; Business Models; Serbia.

1. Introduction

Biomethane is increasingly recognized as a strategic energy carrier with the potential to simultaneously contribute to energy security, climate change mitigation, and sustainable agricultural development. In recent years, global biomethane production has grown significantly, reaching approximately 35–40 billion cubic meters annually, with major contributions from Europe and China (IEA, 2023). Despite this progress, the sector continues to face structural challenges. Conventional development models, primarily focused on energy production, often exhibit low profitability, high capital intensity, and strong dependence on policy support. These limitations indicate that a single-purpose energy orientation is insufficient to ensure long-term sector development. A key limitation of existing approaches lies in their narrow focus on energy outputs, while the broader system interactions between energy, agriculture, and waste management remain underutilized. Biomethane production is inherently linked to agricultural systems, as it relies on organic residues such as livestock manure, crop residues, and agro-industrial waste. At the same time, the by-product of anaerobic digestion—digestate—can be reused as an organic fertilizer, contributing to soil quality improvement and nutrient recycling. This creates the foundation for a circular "waste–energy–nutrient" system. The conceptual structure of this integrated system is illustrated in Figure 1.

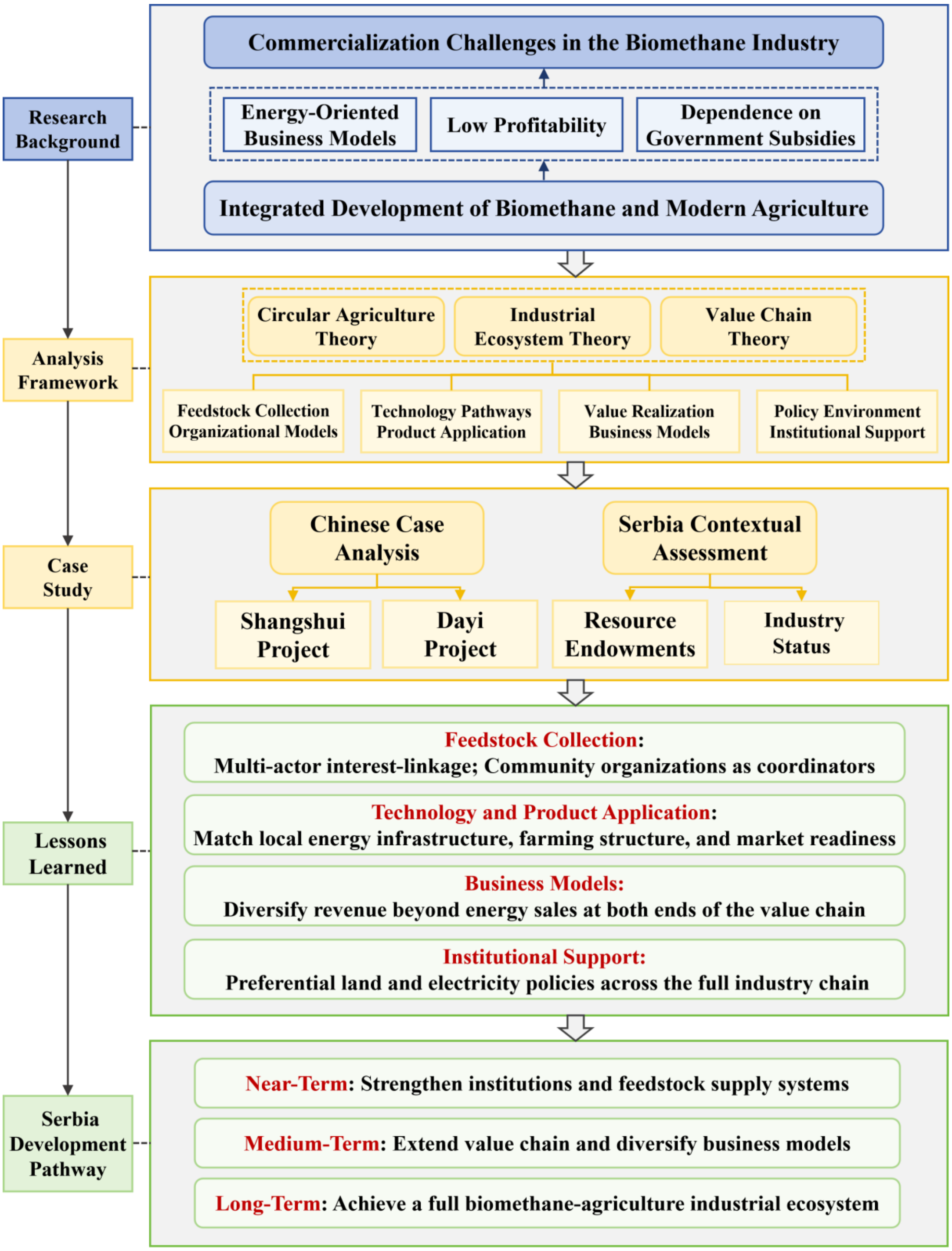

Figure 1 *Integrated biomethane–agriculture system (waste–energy–nutrient cycle)*

This perspective is closely related to the concept of circular agriculture, which emphasizes closed-loop resource flows and the reintegration of waste into productive cycles. Within such systems, biomethane serves as a key nexus connecting environmental management, energy production, and agricultural productivity, as illustrated in Figure 1. In parallel, industrial ecosystem theory highlights the importance of coordinated material and energy flows among multiple actors, while value chain theory focuses on value creation across different stages of production and service delivery. Together, these theoretical perspectives suggest that the performance of biomethane systems depends not only on technological efficiency but also on organizational structures, market mechanisms, and policy frameworks.

Existing literature has predominantly focused on technological aspects of biomethane production, including anaerobic digestion processes, upgrading technologies, and greenhouse gas mitigation potential (IRENA, 2022). However, comparatively less attention has been paid to system-level integration, particularly the coordination of feedstock supply, the development of diversified business models, and the interaction between energy systems and agricultural production. In addition, most studies focus on mature markets, while transitional economies remain underexplored.

China provides an important empirical context for addressing these gaps. Over the past decade, it has developed a range of integrated biomethane–agriculture models that extend beyond energy production to include waste management services, nutrient recycling, and agricultural value-added activities. These models demonstrate how value can be created across the entire system, rather than relying solely on energy sales.

Serbia, in contrast, represents a pre-market context for biomethane development. The country possesses a substantial resource base derived from agricultural activities, as well as an existing biogas sector based primarily on combined heat and power (CHP) systems. However, several structural constraints limit further development. Agricultural production is highly fragmented, resulting in dispersed biomass resources and increased feedstock collection costs. The existing CHP-based model is characterized by limited heat utilization and strong dependence on feed-in tariff schemes. As these support mechanisms are gradually being phased out, the sector faces increasing economic uncertainty.

At the same time, the regulatory and market framework for biomethane remains underdeveloped. Biomethane is not yet fully recognized as a separate energy carrier, and key elements such as upgrading standards, certification procedures, and grid injection conditions are not clearly defined. Furthermore, infrastructure constraints, including uneven gas network coverage, limit the feasibility of large-scale deployment.

Within the broader European context, initiatives such as the REPowerEU Plan and the EU Methane Strategy emphasize the role of biomethane in enhancing energy security and supporting circular economy objectives. These policy directions further highlight the importance of integrating biomethane into both energy and agricultural systems.

In this context, the present study conducts a comparative analysis of biomethane development in China and Serbia. China represents a mature, system-integrated model, while Serbia reflects an early-stage system with significant potential but limited institutional and market development. The objective of this paper is to identify key enabling factors and systemic constraints affecting biomethane development, with a particular focus on organizational structures, business models, and policy frameworks. The findings aim to support the design of development pathways for Serbia and provide insights applicable to other transitional economies.

2. Metodology

This study applies a comparative case study approach to analyze the development of biomethane systems in China and Serbia. The methodology is designed to identify key factors influencing system performance and to assess the transferability of development models between different institutional and economic contexts. The analysis is based on a four-dimensional framework derived from circular agriculture theory, industrial ecosystem theory, and value chain theory. The framework includes: (i) feedstock collection and organizational models, (ii) technology pathways and product application, (iii) value realization and business models, and (iv) institutional support. Two representative case studies from China are selected to illustrate different development pathways, while the Serbian case is analyzed as a pre-market system with existing biogas infrastructure and significant biomass potential. Data sources include literature review, project documentation, and publicly available sector data. The comparative analysis focuses on identifying similarities and differences across the selected dimensions, with particular attention to organizational structures, resource availability, and policy conditions. The results are used to derive development pathways for Serbia and to assess the applicability of integrated biomethane–agriculture models in transitional economies.

3. Case Studies: Integrated Biomethane–Agriculture Systems in China

3.1 Overview of Case Studies

China has developed a range of integrated biomethane–agriculture systems that illustrate the transition from waste treatment–oriented models toward system-based approaches combining energy production, agricultural services, and resource recycling.

To analyze these developments, a four-dimensional framework is applied, focusing on: (i) feedstock collection and organizational models, (ii) technology pathways and product application, (iii) value realization and business models, and (iv) institutional support.

The selected case studies represent two distinct but complementary development pathways. The Shangshui project demonstrates a large-scale, straw-based biomethane system relying on coordinated feedstock aggregation, while the Dayi project illustrates a service-oriented model integrating livestock waste management with agricultural production systems.

3.2. Case Study: Shangshui Project

The Shangshui biomethane project, located in Henan Province, represents a large-scale agricultural waste utilization system based on crop residues, primarily maize straw. The project processes approximately 200,000 tons of straw annually and produces around 18.8 million m^3 of biomethane, along with organic fertilizer as a by-product.

From the perspective of feedstock organization, the project addresses the challenge of dispersed smallholder agriculture through a coordinated collection model involving energy enterprises, local governments, and village-level actors. This multi-actor approach enables large-scale feedstock aggregation while reducing transaction costs and ensuring stable supply.

In terms of technology and product application, the project uses dry anaerobic digestion adapted to straw-based feedstock, producing biomethane for both grid injection and direct industrial use. Digestate is processed into organic fertilizer and applied to nearby agricultural land, supporting nutrient recycling.

The business model is based on diversified revenue streams, combining biomethane sales with organic fertilizer production. Institutional support has facilitated initial investment, while ongoing operation increasingly relies on market-based mechanisms.

Overall, the Shangshui project demonstrates how coordinated feedstock supply, appropriate technology selection, and diversified outputs can support the development of integrated biomethane–agriculture systems.

3.3. Case Study: Dayi Project

The Dayi biomethane project, located in Sichuan Province, represents a livestock-based system focused on the integrated management of manure from large-scale pig farming. The project processes organic waste from agricultural production and converts it into biomethane and organic fertilizer.

Unlike the Shangshui model, the Dayi project emphasizes a service-oriented approach, providing waste treatment solutions for livestock producers while supporting agricultural production through nutrient recycling. This model strengthens the link between energy production and agricultural value chains.

From the perspective of technology, the project uses wet anaerobic digestion suitable for high-moisture feedstock. The produced biomethane is used locally, while digestate is treated and applied as organic fertilizer within surrounding agricultural systems.

The economic model combines waste treatment services, biomethane utilization, and agricultural value-added activities, enabling diversified income streams. Institutional support plays an important role in facilitating coordination between agricultural producers and energy operators.

The Dayi project illustrates an alternative development pathway in which biomethane systems function as service platforms integrating waste management and agricultural production.

4. Serbia: Contextual Assessment and Pathway Design

4.1. Current Status and Resource Assessment

4.1.1. Resource Base and Existing Infrastructure

Serbia represents a pre-market context for biomethane development, characterized by significant biomass availability and an existing biogas sector, but without an operational biomethane production model. The country possesses substantial feedstock resources suitable for anaerobic digestion, including livestock manure, crop residues, agro-industrial by-products, and biodegradable municipal waste. National assessments estimate a technical biomethane potential of approximately 4.3–7.8 TWh per year, corresponding to about 15–28% of current natural gas consumption.

An overview of the main types of feedstocks available for biomethane production in Serbia, along with their key characteristics and estimated quantities, is presented in Table 1.

Table 1. *Overview of available feedstocks for biomethane production in Serbia*

Feedstock type	Substrate	Estimated quantity (t/year)	C/N ratio	Moisture [%]	Biogas yield (m^3/kg VS)
Municipal OW	Household OW	526,918.08	15.45	70.00	0.65
	Wastewater sludge	32,932.38	6–12	75–85	0.38
Livestock manure	Cattle manure	10,884,466.67	3.80	78.20	0.20–0.30
	Pig manure	4,668,800.00	10.00	82.50	0.25–0.50
	Poultry manure	1,082,130.00	6.10–9.10	13.33	0.36
Crop residues	Maize residues	2,889,154.10	52.00	13.00	0.26
	Wheat residues	1,458,208.20	92.72	10.80	0.35–0.45
	Sunflower residues	327,318.80	48.00	12.00	0.25
	Soy residues	254,003.60	28.00	12.00	0.24
Agro-industrial waste	Winery waste (pomace)	44,164.88	22–30	55–70	0.20–0.30

Serbia has developed a modest but relevant biogas infrastructure that provides a technological foundation for future upgrading. Approximately 43 biogas plants are currently in operation, primarily utilizing agricultural residues and livestock manure. These facilities operate predominantly under the combined heat and power (CHP) model, producing electricity and heat from biogas. In this context, their historical development has been closely linked to policy support mechanisms, particularly feed-in tariff schemes for renewable electricity generation.

However, many of these plants are expected to lose tariff eligibility in the coming years as support schemes expire. Consequently, this transition may significantly reduce revenue stability and create additional financial pressure on plant operators. At the same time, it opens a potential pathway for retrofitting existing facilities with upgrading technologies to produce biomethane, thereby enabling a shift from electricity-focused utilization toward higher-value energy applications, provided that suitable regulatory and market frameworks are established.

4.1.2 Feedstock Collection and Organizational Constraints

Despite the favorable resource base, feedstock mobilization faces significant structural barriers. Serbian agriculture is characterized by fragmented landholdings and a large number of small and medium-sized farms, leading to dispersed biomass resources. As a result, this spatial fragmentation increases transportation costs and complicates the logistics of feedstock collection.

Unlike regions with centralized livestock production or large agricultural cooperatives, Serbia lacks well-developed aggregation mechanisms capable of ensuring a stable and predictable feedstock supply. In practice, existing biogas plants typically rely on bilateral contracts with nearby farms and agro-industrial facilities, which limits both flexibility and scalability. Seasonal variability of agricultural residues further complicates supply planning.

These collection bottlenecks result in elevated transaction costs across the biomass supply chain. Consequently, the cost of organizing feedstock transport and coordination can represent a significant share of total operating expenses, reducing the economic attractiveness of large-scale biomethane facilities. Therefore, the absence of cooperative logistics systems and centralized biomass markets represents a key organizational barrier.

Digestate management also influences system performance. While digestate can be utilized as an organic fertilizer, effective recycling depends on local agricultural practices, regulatory requirements, and transport distances. In the absence of coordinated nutrient management systems, digestate handling may become a logistical burden rather than an additional revenue stream.

4.1.3 Market, Regulatory, and Infrastructure Conditions

Institutional and market conditions for biomethane development in Serbia remain underdeveloped. Biomethane is not yet explicitly defined within national energy legislation, and there are no dedicated support schemes or guaranteed off-take mechanisms for renewable gas. As a result, investors face significant uncertainty regarding pricing, certification, and long-term market access.

Market demand for biomethane is also unclear. Although potential applications exist in natural gas substitution, industry, and transport, there are currently no established contractual frameworks or incentive mechanisms to stimulate renewable gas consumption. This situation contrasts with the earlier and more structured support provided to biogas-based electricity generation.

Infrastructure constraints represent one of the most significant barriers. Serbia possesses an established natural gas transmission and distribution network; however, its geographic coverage is uneven. Consequently, many rural areas with high agricultural biomass potential remain located outside densely served gas corridors. The distance between prospective biomethane production sites and existing pipelines can substantially increase connection costs and reduce project feasibility.

Furthermore, technical and regulatory requirements for biomethane grid injections, such as gas quality standards, pressure compatibility, and metering systems, have not yet been fully defined. This lack of clarity further complicates project development and investment decision-making. In regions without pipeline access, alternative utilization pathways such as local heat supply, compressed biomethane for transport, or decentralized energy systems would require additional infrastructure investments.

Overall, Serbia’s current status can be characterized as an early transitional stage of biomethane development, in which essential components, including biomass resources, biogas production experience, and gas infrastructure, exist but remain insufficiently integrated. Therefore, the main constraints are organizational, regulatory, and economic rather than technological, indicating that coordinated institutional action and system-level planning are necessary for large-scale deployment.

4.2 Lessons and Insights from China's Experience for Serbia

This section evaluates the applicability and reference value of China's practical experience for Serbia's integrated development pathway of biomethane and modern agriculture across four dimensions: feedstock collection and organizational models, technology pathways and product application, value realization and business models, and institutional support.

4.2.1 Feedstock Collection and Organizational Models

The Shangshui Project and the Dayi Project provide important references from the perspectives of crop cultivation and livestock farming respectively. The Shangshui Project established a feedstock collection and storage model led by energy enterprises, coordinated and supported by township governments, organized and mobilized by village collectives, and guided by locally influential community figures. Its core strength lies in fully leveraging the organizational and coordinating role of individuals with credibility and mobilization capacity within rural acquaintance-based social networks, achieving high collection and storage efficiency at relatively low institutional cost. Serbian rural communities similarly possess local social networks, and village-level cooperatives, local agricultural associations, and community leaders generally command considerable organizational mobilization capacity and credibility in rural affairs. In advancing the organization of feedstock collection and storage, these community forces can be incorporated into the coordination framework of feedstock supply networks, thereby reducing the transaction costs arising from direct engagement with individual farmers and enhancing both the organizational efficiency and supply stability of feedstock collection and storage operations.

The Dayi Project provides a reference model for the collection and organizational approach applicable to livestock waste-based feedstocks. By offering livestock farms waste treatment services at rates below market prices, the project established a mutually beneficial relationship between energy enterprises and livestock farm operators, enabling farms to resolve their manure compliance disposal challenges at low cost while providing the enterprise with a stable feedstock supply and upstream service revenues. As Serbia advances its EU candidate country accession process, the gradual alignment of environmental regulations is expected to intensify policy pressure on livestock farms to manage manure disposal in compliance with regulatory standards. In regions with concentrated livestock farming operations, the Dayi model of exchanging low-cost treatment services for a stable feedstock supply is therefore likely to hold considerable reference value.

4.2.2 Technology Pathways and Product Application

The selection of production processes and product utilization approaches should be aligned with local energy infrastructure conditions and agricultural production structures. In regions where gas pipeline networks are not yet well-developed, biogas-based electricity generation or direct biogas supply to nearby users represents a more pragmatic option, whereas in regions with relatively favorable infrastructure conditions and robust industrial gas demand, the gradual advancement of biomethane purification and grid injection or direct supply to industrial users can be pursued. With regard to by-product utilization, both case studies demonstrate that incorporating digestate and slurry into the agricultural production system constitutes a critical mechanism for enhancing project economic viability and achieving systemic material cycling. The agricultural socialized service experience of the Dayi Project is of particular reference value: through professional services including soil testing and formula fertilization and digestate-based farmland application, it assists farmers in improving soil quality without increasing their fertilization costs. It is noteworthy that the value realization of by-products is highly dependent on the level of awareness and willingness to adopt organic fertilizers among farmers and market actors, rendering demonstration promotion and market cultivation of considerable importance.

4.2.3 Value Realization and Business Models

The Shangshui and Dayi projects present distinctly different yet mutually complementary business models. The sustainability of the product sales model depends to a considerable extent on local market supply-demand conditions and market receptivity. In contexts where the local gas supply-demand gap is substantial and the proportion of cash crops within the local cropping structure is high, the product sales model may be prioritized for exploration, with by-product value addition achieved through organic fertilizer sales. The service-led model, by contrast, relies on the regional livestock industry's manure disposal demand and the number of large-scale farming entities in the vicinity: the former provides a stable feedstock supply and service clientele for upstream waste treatment fee collection, while the latter provides a sustainable absorption market for downstream digestate formula fertilization services. Where local livestock farming is concentrated, manure disposal pressure is considerable, and large-scale farming entities exist in the surrounding area, the service-led model is likely to be more applicable.

The commercial sustainability of biomethane engineering projects fundamentally depends on whether revenue channels beyond energy product sales can be established at both the upstream and downstream ends of the industry chain. Models relying solely on energy product sales revenues face widespread profitability challenges against the backdrop of subsidy phase-out, and it is precisely through the extension toward waste treatment services and agricultural value-added services that a stable and diversified revenue structure can be constructed.

4.2.4 Institutional Support

The practical experience of both case studies demonstrates that institutional support constitutes an essential guarantee for the successful implementation of the integrated development model of biomethane and modern agriculture. Given the high upfront investment requirements of biomethane engineering projects, relying solely on market-based financing channels is unlikely to effectively catalyze industry initiation, and dedicated startup funding represents a necessary condition for lowering the barriers to private capital entry. At the same time, the application procedures, approval processes, and high holding costs associated with industrial land classification significantly suppress private capital investment willingness. At the policy design level, Serbia should explicitly recognize biomethane engineering projects centered on waste resource utilization as agricultural-attribute projects, extending corresponding preferential treatment in land use approval and electricity pricing. Furthermore, the focus of policy support should be extended to encompass the full industry chain. China's existing policy instruments are predominantly concentrated at the engineering construction end, with insufficient incentives for the green value realization of energy products and the agricultural utilization of by-products. In its policy design, Serbia should extend policy incentives to cover digestate farmland application, rewards for organic fertilizer substitution of chemical fertilizers, and support for agricultural socialized services.

4.3 Development Pathways for Serbia

Based on the comparative analysis and the current conditions of the Serbian biomethane sector, a phased development pathway is proposed, focusing on the progressive integration of biomethane systems with agriculture and waste management.

Short-term (0–3 years): Establishing the foundation

In the initial phase, priority should be given to improving feedstock availability and operational efficiency within existing biogas systems. This includes the development of feedstock aggregation mechanisms, particularly in regions with fragmented agricultural structures, and the optimization of existing combined heat and power (CHP) plants.

Given that a significant number of biogas facilities in Serbia are expected to gradually lose feed-in tariff support in the coming years, there is a need to explore alternative revenue streams. This includes improved utilization of heat, development of local energy services, and initial steps toward biogas upgrading.

At the institutional level, the establishment of a clear regulatory framework for biomethane, including standards for upgrading, certification, and potential grid injection, represents a critical prerequisite for further development.

Medium-term (3–7 years): System integration and market development

In the medium term, the focus should shift toward the integration of biomethane production with agricultural and waste management systems. This includes the expansion of feedstock supply networks, the development of coordinated logistics systems, and the strengthening of links between biogas plants and agricultural producers.

The introduction of diversified business models is essential in this phase. In addition to energy production, biomethane systems can provide waste treatment services, organic fertilizer products, and support for sustainable agricultural practices.

Infrastructure development, particularly related to gas networks and upgrading facilities, will play an important role in enabling the use of biomethane in energy and transport sectors. Policy support should transition from investment-based incentives toward mechanisms that encourage market-based operation and system integration.

Long-term (7+ years): Market maturity and full system integration

In the long term, biomethane development in Serbia should evolve toward a fully integrated system in which energy, agriculture, and waste management are interconnected.

Biomethane can become a standard component of the energy system, with established pathways for grid injection, transport use, and industrial applications. At the same time, circular agriculture models can be strengthened through systematic nutrient recycling and the widespread use of organic fertilizers.

The development of stable market mechanisms, including pricing structures and certification systems, will be essential to ensure long-term economic sustainability. At this stage, biomethane systems are expected to operate with limited dependence on direct policy support, relying instead on integrated value creation across the system.

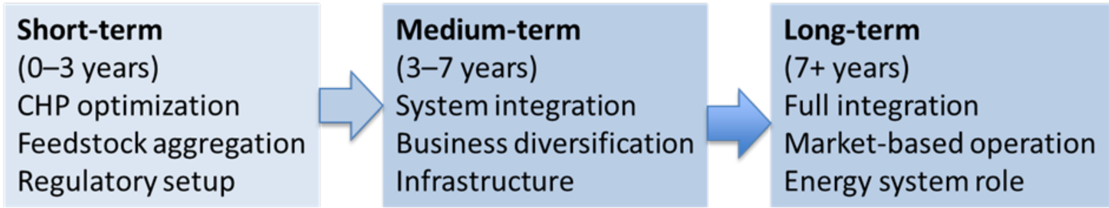

Figure 2. *Development pathway for biomethane in Serbia (phased transition from CHP-based systems to integrated market-based systems)*

The proposed phased development pathway is summarized in Figure 2. The transition from the current CHP-based model toward integrated biomethane systems requires a gradual and coordinated approach, in which technical, organizational, and institutional elements evolve simultaneously.

In the short term, the focus is on improving the efficiency of existing biogas systems and establishing the regulatory framework necessary for biomethane development. In the medium term, system integration becomes the central objective, with stronger linkages between energy production, agriculture, and waste management, supported by diversified business models. In the long term, biomethane is expected to become fully integrated into the energy system, operating under market-based conditions and contributing to broader sustainability goals.

5. Conclusion

This study examined the development of biomethane systems through a comparative analysis of China and Serbia, using a four-dimensional framework that integrates circular agriculture, industrial ecosystem, and value chain perspectives.

The results show that biomethane systems based solely on energy production face structural limitations, including low profitability and dependence on policy support. In contrast, integrated models linking waste management, energy production, and agricultural systems enable more stable feedstock supply, diversified revenue streams, and improved overall system performance.

The analysis of Chinese case studies demonstrates that successful development depends on coordinated feedstock aggregation, appropriate technology selection, and the integration of biomethane production with agricultural value chains. These findings highlight the importance of system-level approaches rather than isolated project-based solutions.

In Serbia, despite a solid resource base and an established biogas sector, biomethane development remains constrained by fragmented agricultural structures, underdeveloped regulatory frameworks, and limited system integration. The proposed phased development pathway emphasizes the need for gradual transition from electricity-oriented models toward integrated biomethane–agriculture systems.

Overall, the study contributes to understanding how biomethane can evolve from a subsidy-dependent energy activity into a key component of circular and sustainable agricultural systems, particularly in transitional economies.

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