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Review

China's Biogas Industry's Sustainable Transition to a Low-Carbon Plan—A Socio-Technical Perspective

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Abstract: China's biogas industry has experienced ups and downs over the past two decades, with various challenges pointing to misplaced expectations that biogas technology is overly focused on energy production. With the promotion of China's low-carbon strategy, a more rational and sustainable transformation strategy is crucial for the development of the biogas industry. To elucidate the sustainable development process of the biogas industry, this study applies the socio-technical transition theory and the strategic niche management (SNM) approach to understand the multi-regime interactions of biogas systems and their possible future paths. At present, the Chinese biogas industry needs to abandon the expectation of energy recovery and establish the expectation of multi-functional combination, especially including nutrient cycling. This study proposes a sustainable transformation path for the biogas industry and predicts three phases based on the type of socio-technological transformation path: a transformation path to 2030 to promote niche innovation and develop core technologies; a reconfiguration path from 2030 to 2050, which will require a lot of trials and errors; and the expansion of market share in 2050 through technology replacement. This study highlights the importance of niche experimentations and broad advocacy coalitions for the biogas industry. This research also illustrates how the transformation of China's biogas industry can be achieved through incremental innovation with consistent policy support.

Keywords: biogas transition; transition pathway; multi-function; socio-technical; biogas niche; low-carbon strategy

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1. Introduction

Under the pressure of climate change, the need for low-carbon transitions is critical [1]. However, sustainable low-carbon transitions between countries and domains have non-linear dynamics and involve complex social processes [2]. China proposed an ambitious climate policy in 2020, with "30–60" carbon peak and neutrality targets, but it is still a difficult challenge to achieve sustainable transitions according to the low-carbon strategy roadmap [3]. The high penetration of renewable energy is essential to achieve this goal [4]. Currently, China's renewable energy development relies on the promotion of solar photovoltaic (PV) and wind power [5]. As a backup resource, bioenergy is the most attractive source of renewable energy [6], due to its indispensable role in a net zero world [7]. As a gaseous bioenergy resource, biogas should play a role in the energy transition [8,9]. In rural areas, biogas was once considered an important part of the energy supply [10]. However, after decades of practice, it has not achieved the desired effect in terms of economic and commercial viability [11]. According to the "Implementation Plan for Agricultural and Rural Carbon Reduction and Sequestration ", biogas was introduced as an alternative renewable energy in 2022. However, the "Implementation Opinions on Accelerating Rural Energy Transformation and Development and Helping Rural Revitalization" in 2022 shows that the priority of rural clean energy is solar PV, while biogas technology is emphasized as an application of biomass resources. There is no doubt that China's biogas industry has come to a crossroads of sustainable development, but it is largely unknown how the interaction between policy and biogas technology function can accelerate the transition under the low-carbon strategy.

Accompanied by the "Rural Household Biogas State Debt Project" issued in 2003, the number of household digesters has developed rapidly [12], from fewer than 10 million in 2000 to 41.933 million in 2015. However, negative growth started in 2016 and this number decreased to 30.077 million in 2020 (Figure 1). The serious collapse of the household biogas market is mainly due to the mixture of the optimization of the agricultural industry structure [12–16], the lack of follow-up services and management [15–17], the growth of the rural economy [16,18], and the largest urbanization process in human history in recent years [12,13,16,19]. Currently, rural clean energy is being replaced by rural power grid upgrading projects and distributed PV generation [20–23]. Since the release of the "National Rural Biogas Project Construction Plan", the policy has shifted from household digesters to biogas projects [13,24]. The number of biogas projects, like a raging fire, increased from fewer than 10,000 in 2005 to 113,440 in 2016 (Figure 2), mainly small-scale [25]. The significant growth of biogas projects may be due to the development of intensive livestock production [12,26,27]. However, due to high operation and maintenance requirements, these simple biogas plants cannot guarantee biogas supply [10,26,28], and hardly benefit from energy recovery [10,29]. A large volume of biogas slurry and residues becomes waste, leading to secondary pollution [29], and the potential emission reduction benefits are not as enticing as free-riding for companies [30]. Together, these components lead to a severe collapse of the biogas plant market. It was predicted that by 2020, there would only be 93,481 biogas projects left in China.

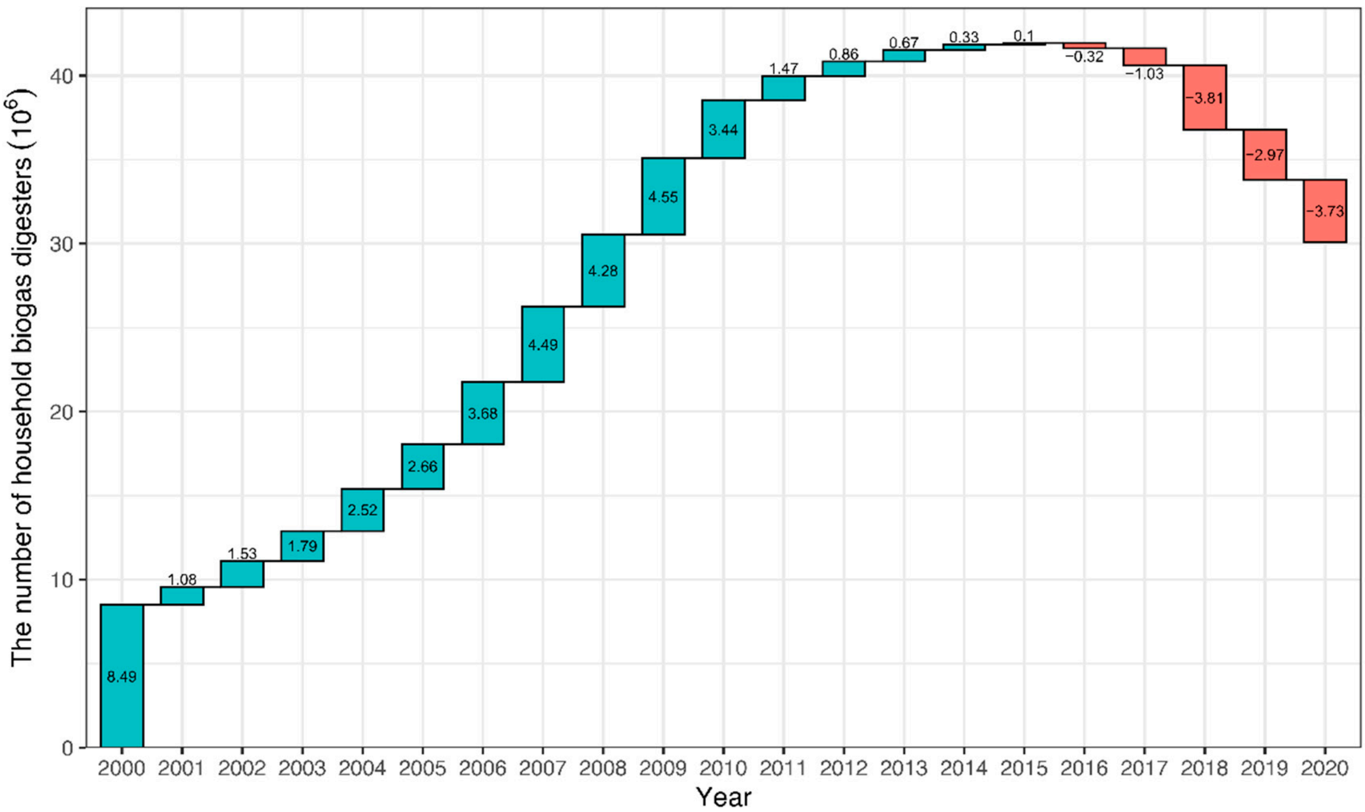

Figure 1. Trend of household biogas digesters (2000–2020) (source: [31–33]).

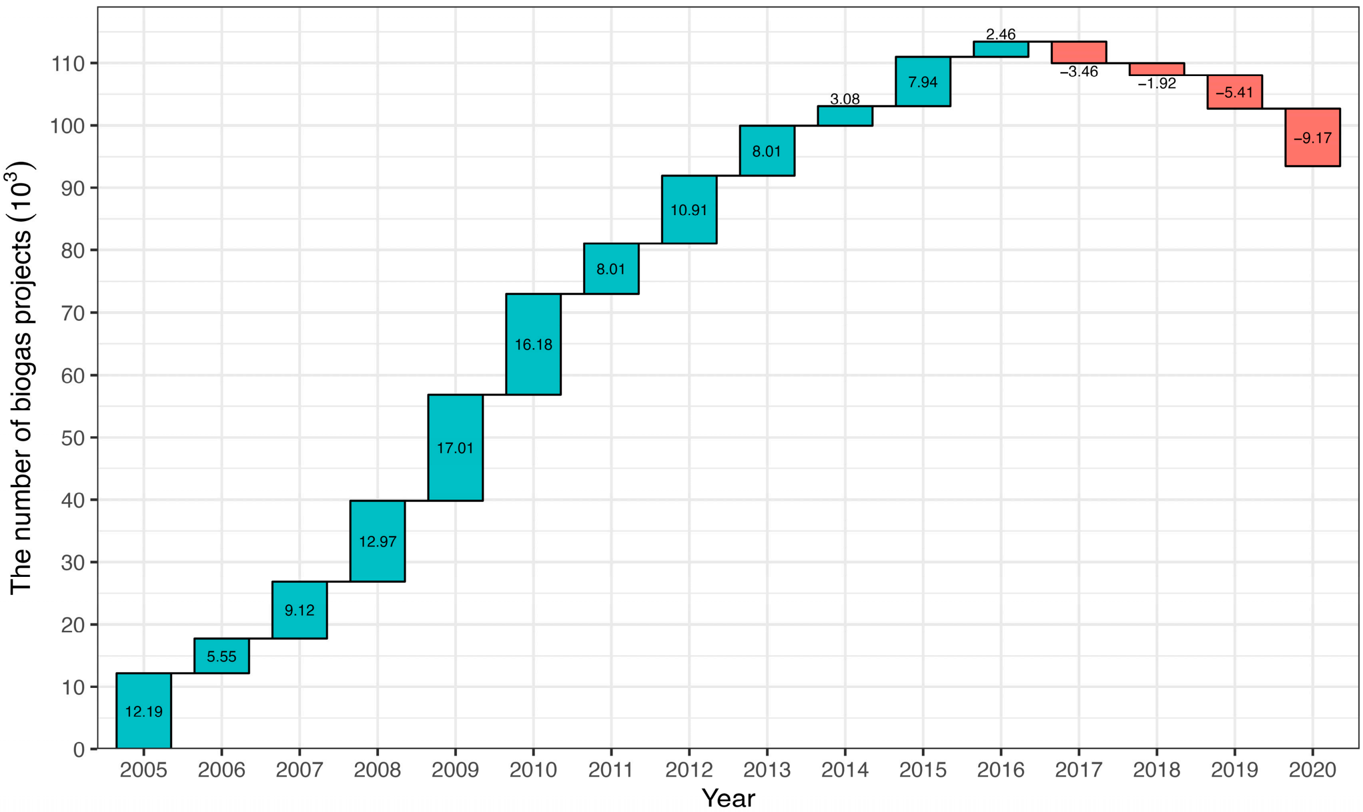

Figure 2. Trend of biogas projects (2005–2020) (source: [31,33]).

In 2015, a biogas industry transition was proposed by the Chinese government. "The working plan of upgrading and transforming rural biogas projects" showed that the budget investment of the Chinese central government focused on supporting the construction of large-scale biogas projects, including 65 large-scale bio-natural gas pilot projects. In fact, there were many reasons for the government to upgrade the biogas industry by increasing the scale of projects. First of all, the number of household digesters is irreversibly reduced and the development of biogas projects is stagnating [34]. Secondly, a large number of studies have shown that larger-scale biogas projects are more valuable [12,25,35,36]. Additionally, the large-scale production of biogas purified into bio-natural gas is technically feasible and has been widely used in Europe [37]. However, this transition is still not very encouraging [3,38–40], suffering from excessive overload demand for raw materials and land. Paradoxically, crop production and livestock production are decoupled in China [41,42], and the economic benefits are still not clear [40,43,44]. Now, the transition and upgrading of the rural biogas sector includes the following aspects: resource utilization of livestock and poultry manure, bio-natural gas, rural energy transition under "Rural Revitalization", and improvement of the rural residential environment.

The non-linearity trajectories of the biogas industry in China indicate that there have been various utilization types of gaseous bioenergy based on anaerobic digestion. As a boundary-crossing innovation in the energy and agricultural sectors, it faces different regime demands [8], which can be conceptualized as a multi-regime interaction [45]. The energy sector competes with the generation of electricity, heat, and natural gas [46], while the agricultural sector is also influenced by the crop and livestock sectors [47]. In China, biogas production is manure-based (Figure 3), indicating the priority of waste management, but energy recovery is still the most attractive function [16,28]. At the same time, the presence of digestate means that biogas technology must take on a nutrient recovery function [48,49]. The emission reduction function will gradually come to the fore in China's low-carbon strategy. The multi-functionality of biogas technology means that the interesting patterns and allocations are complex and cover a wide range [50]. Globally, biogas technology is still considered a subsidy-driven technology nowadays, and its vulnerability and over-dependence on policy [43] mean that there are insurmountable barriers between the application potential in the biogas sector and the current commercial market [51–53]. Most studies on the development of China's biogas sector emphasize energy production expectations, focus on the current state of the industry and policy, and mainly consider technological maturity, feedstock supply, and local socio-economic issues rather than the multi-agency interaction of biogas functions. A more dynamic view of the biogas transition from a socio-technical perspective could provide new insights into the sustainable development of the biogas industry in China.

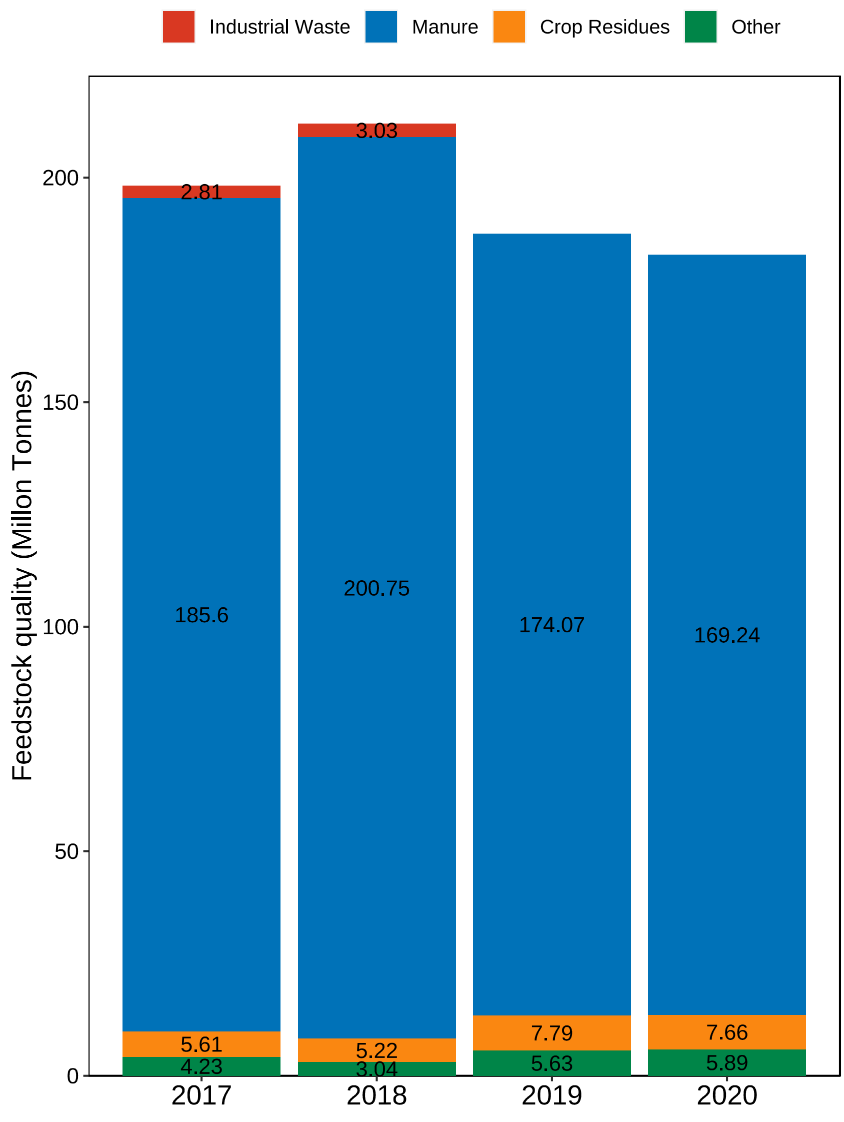

Figure 3. Chinese biogas industry feedstock quality (source: [54]).

As an emerging field of research, sustainability transition is based on a socio-technical system consisting of theoretical frameworks such as strategic niche management (SNM), multi-level perspective (MLP), typology of transition pathways, and technological innovation system (TIS), etc., which are widely used in low-carbon, energy, transportation, agriculture, and so on [55–59]. Previous Chinese industry transition studies focus on new energy vehicles, PV, and electricity [60–62]. Transition research for the biogas industry is applied in European countries such as the Netherlands, Denmark, and Finland [63–66], but few examples of the sustainable transition of the biogas industry in China have been demonstrated. SNM refers to breakthrough innovations that disrupt unsustainable socio-technical systems and ultimately transform societal functions, and can be used to analyze the potential socio-technical regime conflicts [67]. SNM conceptualizes these "protected spaces" as niches, requiring strategic support to avoid premature rejection by investors, customers, and users, while developing the performance, price, and infrastructure of these technologies [68]. Based on a socio-technical framework, biogas technology, which is both environmentally friendly and socially oriented, can be regarded as a novel niche-level technology [36,69,70]. The typology of transition pathways is a classification based on the interaction between socio-technical systems [71], which can provide biogas industry sustainability transition in China. This study, which links the sustainable transition of China's biogas industry with the low-carbon strategy, opens up new perspectives for studying the biogas transition and provides new theoretical foundations for investors and policymakers.

This review describes insights from the SNM framework that address the institutional challenges of the sustainable transition of a niche innovation, the biogas industry in China. The multi-functional portfolio for the sustainable development of biogas in China is summarized in the context of a low-carbon strategy, and this study tries to find the most appropriate path for the socio-technical transformation of the biogas industry in China. The research focuses on manure-based biogas systems, while only part of the results and discussion relate to rural organic waste treatment. The paper is organized as follows. Section 2 outlines the methodology used in the paper, Section 3 outlines a multi-functional portfolio for the sustainable development of China's biogas industry, Section 4 illustrates the transition paths of China's biogas industry, Section 5 is the discussion, and Section 6 is the conclusion.

2. Methodology

2.1. SNM

'Niche' is the core concept of SNM and refers to a 'protected space' [66]. 'Expectation' is an essential mechanism in SNM, plays an important role in emerging technologies, and expresses participants' interpretations of general rules and perceived benefits or risks of a project before it is realized [72]. Experimentation is important for niche creation, and the results of experimentation influence actors' expectations. The dynamics of actors' expectations lead to changes in application domains [73]. Potential partners and stakeholders often view projects from different perspectives and naturally have different expectations. Therefore, the realization of emerging niche technologies most likely results from extensive discussions and efforts to reach a consensus on expectations [72]. As a niche, the potential expectations of regime actors naturally diverge under different pressures [74].

2.2. Typology of Transition Pathways

The typology of pathways in socio-technical transition theory was first proposed by Frank W. Geels and Johan Schot [71]. Five key transition paths are included:

(a) Reproduction process: Without pressure from the landscape, whilst niche innovation possibilities remain, the chances of breakthroughs are narrow. With an absence of real interaction between landscape, regimes, and niche, the socio-technical systems are in a state of self-replication.

(b) Transformation path: When the landscape is more moderate and niche innovations are not adequately developed to exploit the opportunities offered by landscape pressures, actors within the existing regime will redirect their developmental paths and innovation activities to cope with the pressure.

(c) Reconfiguration path: A set of interdependent innovations developed from the niche begin to be used in the regime, replacing the former technology portfolio to solve local problems, which subsequently triggers the restructuring of the underlying regime.

(d) Technological substitution: Disruptive changes at the landscape level that destabilize existing regimes, creating windows of opportunity for niche innovations to break through the resistance to existing regimes and create new ones to replace them.

(e) De-alignment and re-alignment path: Multiple dramatic sudden changes occur in the landscape, increasing the regime problems and leading to a loss of confidence among internal actors. The regime splits and gradually weakens without significant technological substitution, as at the beginning of the split, the niche innovations are not yet well developed. However, this scenario will provide scope for the further development of multiple co-existing and competing niche innovations.

3. Niche and Sustainable Models

3.1. Niches as Units of Sustainable Transition

3.1.1. Definition of Niche: Functionality of Anaerobic Digestion in China

Innovation across multi-regime boundaries has been particularly fruitful in studies of transition experiments [75]. Biogas production technologies based on anaerobic digestion aim to provide sustainable products in a circular economy [70], driven by policy factors such as environment and waste, energy, and climate [50], offering various functions including energy production, resource recovery, bio-waste treatment, biochemical agents, and climate change mitigation [50,70,75]. Biogas technology can, therefore, be regarded as a transboundary innovation across multiple socio-technical systems and can be divided into four expectations based on a functional vision of biogas: waste management, nutrient recycling, energy recovery, and climate benefits.

3.1.2. Regime Pressures and Challenges for Each Mono-Function of Biogas in China

The four functions of biogas offer different visions for investors, with their regime pressures and challenges, respectively (Table 1).

Table 1. Socio-technical regimes of China's biogas transition.

		Normative	Regulative	Cognitive
	Mechanisms Legitimacy	Coercive Legally sanctioned	Normative pressure Morally governed	Mimetic, learning, imitation Conceptually correct
A	Waste Management	Compulsory environmental regulations Reasonable waste management subsidies	Waste management benefits NIMBY	Environmental recommendations
B	Nutrient Recycling	Agricultural compulsory demands Organic farming strongly driving	Benefits of organic farming	Agricultural recommendations
C	Energy Recovery	Renewable energy demand-driven	Benefits of alternative energy	Theoretical energy cost savings
D	Climate Benefit	Compulsory emission reduction credits Reasonable carbon price trading revenue	Pilot climate benefits	Theoretical emission reduction benefits

A. Waste Management

The primary waste management technologies are composting and anaerobic digestion. Economically, composting is cheaper in construction and operation than anaerobic [76]; technically, composting is less difficult and has a higher organic matter decomposition efficiency [76]. Undoubtedly, most companies would prefer composting without external pressure. However, anaerobic digestion is a very effective way to reduce flies and odors, as well as solve the "Not in My Back Yard (NIMBY)" dilemma, which is favored by China's environmental authorities and entrusted to rural habitat improvement campaigns. Consequently, anaerobic technology is more advantageous when there are high subsidies for waste treatment or more obligatory environmental regulation incentives.

B. Nutrient Recycling

Biogas residues are primarily used on agricultural land, reducing the use of synthetic fertilizers by recovering nutrients and making agriculture more sustainable. De facto, residues are considered by-products of biogas production with low market acceptance, which has become a barrier to the sustainable operation of biogas plants [77]. However, as the Earth's nitrogen and phosphorus production resources become limited, more mandatory nutrient recovery strategies will be adopted, making anaerobic technology, with its advantages of more efficient nitrogen and phosphorus recovery, become more attractive [76].

Meanwhile, the strong demand for organic food [8] will drive the production of organic fertilizers to meet organic farming standards [39]. Biogas-coupled agroecosystems are an essential solution for the coupling of cultivation and intensive husbandry [49].

C. Energy Recovery

The conversion of waste into energy through anaerobic digestion is technologically mature and theoretically cost-effective. The purification of biogas into biomethane is a vital aspect of energy recovery via biogas, with China targeting over 20 billion cubic meters of biomethane per year by 2030. However, biogas energy recovery is currently constrained by the high cost of gas production, cumbersome management, and limited policy support. With the growing demand for renewable energy and advances in anaerobic digestion technology, the energy properties of biogas production could become highly profitable and attractive.

D. Climate Benefits

Reasonable utilization of biogas can reduce carbon emissions, the Clean Development Mechanism has a limited number of biogas pilots in China, and real monetary gains from the climate effect still require the establishment and maturation of a national carbon price market. Interestingly, a national carbon emissions trading market was established in 2021, consisting of a national carbon emissions registration system, a trading system, and a greenhouse gas emissions data reporting system of key emissions units. The establishment of a mature carbon trading market will certainly bring additional benefits from CO_2 value added [78]. Meanwhile, the co-production of biomethane and many chemicals such as methanol [79], bioethanol [80], urea [81], formic acid [82], carbon dioxide [83], hydrogen [84], or dimethyl ether [85] could help to decarbonize China. China's carbon peak and carbon neutrality by 2030 and 2060, respectively, along with developed countries' Net Zero 2050 initiative, represent a "window of opportunity" for climate change reform that will ultimately help the biogas industry generate revenue.

3.2. Sustainable Multi-Functional Models

(a) Model A, B Multi-Functional (M_{AB}): Basic Waste Management and Residue Utilization (Figure 4).

In China, biogas technology is mainly used for the treatment of agricultural waste. After anaerobic digestion, a large amount of slurry and digestate is generated, which has been neglected by stakeholders before investment, and eventually, the biogas residue is returned to the land for nutrient recovery. Hence, the Chinese biogas industry is an interaction of at least two regimes, waste management and nutrient recycling, containing both functions A (waste management) and B (nutrient recycling). All sustainable multi-functional combinations of biogas in China are based on the co-existence of A and B.

(b) Model A, B, C multi-functional (M_{ABC}): Utilization of bioenergy functionality under the premise of waste management and residue utilization (Figure 4).

The production of gaseous bioenergy from agricultural waste through anaerobic digestion is the most attractive feature compared to other waste management methods. However, anaerobic digestion for energy is still idealized—accidental leakage or deliberate release of biogas is a common problem in developing countries [86,87]. This energetic portfolio will come to the fore when it economically feasible to produce energy from the waste rather than directly purchasing commercial energy. The multi-functional combination of A, B, and C (energy recovery) can be seen as a positive and sustainable cycle to solve the problem of waste utilization. With the implementation of the M_{ABC} model, the pressure on energy production is reduced, thus improving the diffusion of the biogas system [75].

(c) Model A, B, C, D multi-functional (M_{ABCD}): Bioenergy functionality with consistent carbon price revenues, within the premise of waste management and residue utilization (Figure 4).

Making biogas profitable in all of its functions is the ultimate goal of sustainable biogas development in China. However, this combination can only be achieved if all regulatory dimensions are realized. Once the biogas M_{ABC} model is implemented, the potential benefits of emission reduction are already created. This study defines the full function of M_{ABCD} as the establishment of a carbon emission trading mechanism for the biogas industry, where stakeholders can easily obtain carbon revenues from the carbon price market and ensure maximum profitability of the biogas project by adjusting the operation of the plant according to changes in energy and carbon prices.

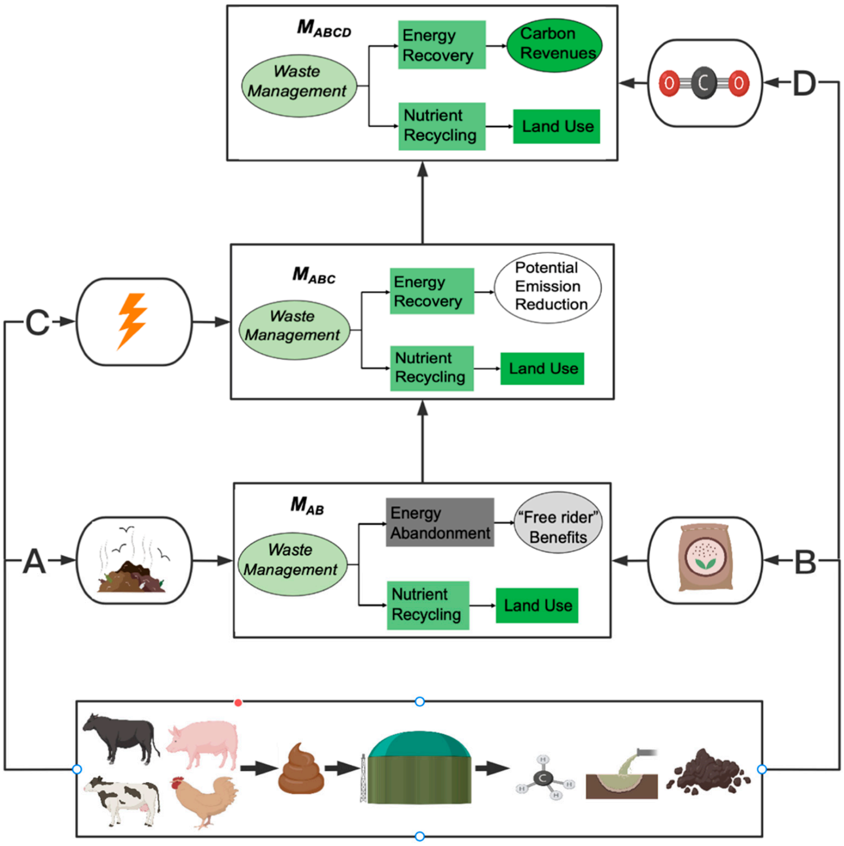

Figure 4. Biogas sustainability multi-functional models.

4. Scenarios of Various Biogas Transition Pathways

Biogas transition under the low-carbon strategy presumes the ultimate achievement of the full-functional model. The regime pressure for each function will influence the low-carbon roadmap. Therefore, the decarbonization 'window of opportunity' years of 2030, 2050, and 2060 will be an important point in the alignment of a sustainable transition pathway for biogas in China. (Figure 5).

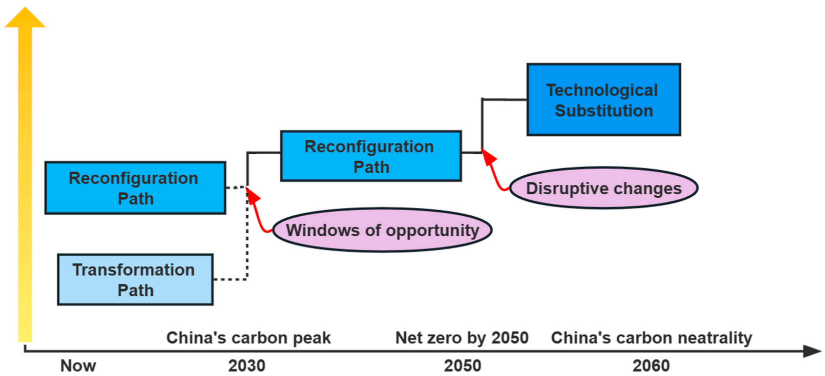

Figure 5. China's biogas sustainable transition pathway roadmap.

4.1. Defining Chinese Biogas Transition Pathways Based on Biogas Development Scenarios in China

Based on the differences in the timing and properties of multi-level interactions, the diverse types of transition pathways developed can be used to study biogas transition pathways in China (Table 2).

(a) Chinese biogas industry reproduction process

Once the government has lost interest in biogas niche innovation and R&D investment, the biogas sector will continue to decline. Stakeholders will lose confidence in the Chinese biogas industry, and there will be no real interaction between landscape, regime, and niche, resulting in little chance of a breakthrough in the biogas industry. This path can be interrupted by breakthrough developments in global biogas socio-technical systems.

(b) Chinese biogas industry transformation path

Considering the lack of regime pressure on the various functionalities of biogas (Table 1), the cost of such a transition is relatively low, and the bottom-up strategy can be partially adopted, with limited practical experiments with biogas technology tailored to local conditions and long-term stable financial and technical support for experimental biogas projects, while the government receives timely feedback on the development of the entire biogas industry and dynamically aligns industry policy support.

(c) Chinese biogas industry reconfiguration path

If regime pressure (Table 1) is not sufficient to achieve the widespread adoption of biogas technology in China, then the government will provide high transition costs, establish different sizes of biogas projects, bear all trial costs and provide subsidies, and make policies for experimentation. For enterprises, premature socio-technical experimentation increases operating costs, and such a practice creates uncertainty for the entire industry, which may lead to company restructuring.

(d) Chinese biogas industry technological substitution

As regime pressures (Table 1) increase, when disruptive changes occur in the energy sector such as extreme energy shortages, biogas will need to be used to fill the energy supply gap. Similarly, as China approaches the point of carbon neutrality, disruptive changes will occur in the climate sector that would force consideration of all possible means to support low-carbon goals, including biogas. Because of the disruptive changes, biogas technology must be applied.

(e) Chinese biogas industry de-alignment and re-alignment path

Investors interested in biogas projects often focus on a mono-function, especially on the most attractive energy property. If the regime pressure for each functionality remains low (Table 1), the energy property of biogas will not meet the profit expectations. Indeed, as a multi-regime industry, biogas investments based on expectations of a single functionality are unsustainable. Failed expectations leave biogas stakeholders confused, and some actors continue to pursue different functionalities of biogas projects due to the significant sunk costs already incurred.

Table 2. The highlights of Chinese biogas transition pathways.

Chinese Biogas Transition Pathways	Highlights
Reproduction process	Abandoned the biogas sector
Transformation path	Incremental innovation strategy
Reconfiguration path	Radical innovation strategy
Technological substitution	Disruptive changes
De-alignment and re-alignment path	Focus on mono-functional properties

4.2. China's Biogas Transition Pathway before Carbon Peak (Now~2030)

The ups and downs of the biogas industry in the first two decades of the 21st century have proven that the expectation of mono-functional properties is not reasonable. The 2015 "Work Plan for the Transformation and Upgrading of Rural Biogas Projects" revealed that biogas will be upgraded in the direction of large-scale development, integrated utilization, and cost-effectiveness. Therefore, the possibility of focusing on the mono-function of biogas development is almost eliminated, and the de-alignment and re-alignment path will not be taken before 2030. Considering that China's vital energy source, coal, will still be available for almost 40 years, with the explosive development of PV and wind energy in China, disruptive changes and energy shortages are almost non-existent. While carbon neutrality is nearly 40 years away, a moment of technological substitution for climate change mitigation through extensive biogas diffusion is far from imminent. Nevertheless, completely withdrawing support for the development of biogas and abandoning niche experimentation, a transition path that replicates existing processes and creates a dilemma similar to the Dutch biogas transition in 2000, cannot be accepted by a government with a top-down national policy overall.

Support and experimentation for biogas projects are essential at this stage, but there are still two paths: the reconfiguration path of massive experimentation and the transformation path of limited experimentation, the former as radical innovation and the latter as incremental innovation.

4.2.1. Radical Innovation Scenario (Now~2030)

Characteristics: Taking a reconfiguration path, radical innovation, massive piloting of M_{AB}, M_{ABC}, M_{ABCD}, medium- to long-term policy agenda, higher transition costs.

A reconfiguration pathway will be adopted until 2030, with numerous trials of various multi-functional models of biogas projects funded, screening out the biogas projects that are worthy of promotion, followed by massive promotion of pilot projects.

The government has a stable policy and financial support for the biogas industry, maintains confidence in the success of the biogas transition, and focuses on the high-cost technologies associated with anaerobic digestion and large-scale industrial pilot projects, which has a positive impact on the development of Chinese biogas industry. However, numerous industrial pilots are a strategy to extend the biogas value chain by encouraging all biogas projects to develop different multi-functional models. When regime pressure remains low, idealistic attempts at socio-technical experimentation are prone to failure, and stakeholder confidence in the biogas industry may be undermined by trial and error.

4.2.2. Incremental Innovation Scenario (Now~2030)

Characteristics: Taking a transformation path, incremental innovation, promoting M_{AB}, limited piloting of M_{ABC}, M_{ABCD}, short-term policy agenda, lower transition costs.

A transformation pathway will be adopted until 2030, with a conservative development strategy of promoting the basic model and limited piloting of advanced models. The incremental innovation strategy is determined by the low level of regime pressure (Table 1). At present, the carbon tax market is immature, gaseous bioenergy is non-profitable, the organic food market is immature, and the environmental pressures on farming remain unclear. The government needs to guarantee a certain quantity of pilots of basic multi-functional models that could help the niche to be studied and nurtured. The government should constantly reorient its support for practical experiments according to the changes in functional expectations of the biogas industry, conduct techno-economic analyses of experimental commercial projects to obtain feedback, support fundamental research on various multi-functional properties of biogas, and robustly and modestly support the application of state-of-the-art multi-functional models.

4.2.3. Differences in Emission Reduction and Economy under Different Strategies (Now~2030)

Referring to the "China Biogas Industry Double Carbon Development Report" published by the China Biogas Society (Table S1), the biogas production, emission reduction, and economic scenarios under different strategies are calculated (Table 3).

Table 3. Emission reduction and economy under different strategies.

Scenario	Biogas Production (Billion m^3)	Emission Reduction (Mt CO_2e)	Required Subsidies (CNY Billion)
2030 RS	44.78	80	273.75
2030 RI	53.82	96	335.66
2030 II	4.78	9	23.21

Abbreviations in Table 3. Mt, million tons; CO_2e, carbon dioxide equivalent; CNY, Chinese yuan renminbi; RS, report scenario; RI, radical innovation; II, incremental innovation.

From Table 3, it can be seen that a radical innovation strategy by 2030 could lead to a 96 Mt reduction in CO_2e in 2030, while an incremental innovation strategy would reduce Mt CO_2e. However, from an investment perspective, to achieve the radical innovation strategy, the Chinese government needs to invest CNY 335.66 billion by 2030, which is unrealistic. In 2017, the Chinese central government subsidy for biogas was only CNY 2 billion, which is close to the investment of CNY 23.21 billion by 2030 for the incremental innovation strategy. Therefore, it is a more reasonable strategy to adopt the incremental innovation strategy and change the expectation of investment in the biogas industry.

4.3. China's Biogas Transition Pathway before Carbon Neutrality (2030~2060)

After China's carbon peak in 2030, it will confront the issue of carbon neutrality and accelerate the pace of a zero-carbon society, adopting a more radical low-carbon innovation paradigm than it did before 2030. Thus, a reconfiguration pathway must be taken in the 2030s, initially with a massive deployment of biogas projects for multi-functional or full-functional experiments, which could last for decades until regime pressures become unambiguous.

From a landscape perspective, the global decarbonization roadmap, especially in developed countries, will achieve net zero emissions by 2050 [78]. Studies suggest that a carbon-neutral electricity system based on 100% renewable energy is technically and economically feasible globally by 2050 [88]. This study assumes that by 2050, all existing new energy technologies, including biogas, will have broken through the niche level and will be free from subsidies to enter the large-scale commercial level. Therefore, the Chinese biogas niche, at the local level, will take reference from global niches, which are the Western countries that have already achieved carbon neutrality, by incorporating effective techno-economic models, localizing them, and subsequently upgrading the existing biogas projects on a large scale. The reconfiguration path for biogas in China will, thus, be halted around 2050, and the era of technological substitution will commence until China achieves carbon neutrality by 2060. By 2060, the biogas sector could reduce emissions by 318.75 Mt CO_2e, requiring at least CNY 700.59 billion of investment from the Chinese government (Table S1).

China's biogas sustainable transition pathway is as follows: 2030–2050, taking the reconfiguration path, emphasis attempts on M_{AB}, M_{ABC}, and M_{ABCD} models; 2050–2060, taking technological substitution, mainly substituted M_{ABCD} model, partly substituted for M_{AB} and M_{ABC} models.

5. Discussion

5.1. The Importance of Biogas Niche Experiments and Expectations

5.1.1. Can China Manage without Biogas Technology? From Niche Experiments

Cultivating a niche is a long-term process, and it is difficult to predict when it will develop into a dominant position. For example, in 2009, the installed capacity of PV in China was only 2.5 MW, or less than 0.01%. Now, more than a decade later, in 2022, the installed PV capacity of China has reached 292.61 GW, accounting for 15.31%. The growth of the PV niche comes from the continued investment in the renewable energy sector [89]. R.P.J.M. Raven and F.W. Geels compared the Danish and Dutch biogas markets and found that the difference was that the Netherlands had stopped supporting niche experiments with anaerobic digestion. From an SNM perspective, this stops internal learning and feedback, which means that when the technology is applied again, it takes time and effort to figure it out from scratch, which is strongly advised against in a niche strategy. Therefore, the only way to ensure a niche market for biogas technology is to experiment consistently and steadily [73].

How to conduct a rational niche experiment requires taking into account the expectations and interests of biogas stakeholders and creating a broader coalition to attract the attention of people from different industries to stimulate such a niche market. Such a coalition should include biogas operators, researchers, and potential stakeholders from different regions [23]. The Danish government has adopted a bottom-up strategy to create a dedicated social network to make biogas plants sustainable by stimulating interaction and learning between different groups in society [35].

At the same time, there is a decoupling between the laboratory setting of biogas technology and the practical real-world application of the technology [90]. Most of the information on biogas production is generated through laboratory-scale investigations rather than commercial plants, which weakens the ability of investors to accurately assess the commercial value of biogas projects [91]. A large number of biogas projects use outdated technologies, and the lack of experimental data inhibits reliable techno-economic and sustainability analysis [90], so internal learning feedback from experiments can promote innovation in biogas niches.

5.1.2. Expectation of Investment in Energy Recovery Should Be Abandoned

Although global policymakers and investors see the potential of biogas as a sustainable product, it is difficult to realize in practice. Apart from energy recovery, the other benefits of anaerobic digestion have positive externalities only when institutional constraints are low [92,93], and have potential economic benefits only for low-income rural areas [94]. Therefore, most policies and investors still tend to regard biogas as an energy product and respond according to its economic profitability and energy market competitiveness [12].

There is still optimism about anaerobic digestion for biogas production and insistence that large centralized biogas plants can benefit from economies of scale, and it is doubtful that such a promise will materialize in China in the short term. In Europe, a pioneer in biogas upgrading, energy production costs remain high and biomethane upgrading is heavily dependent on subsidies [78]. From an SNM perspective, gaseous bioenergy is an immature renewable energy sector whose transition process is inevitably challenged by the technological "lock-in" of conventional energy sources and the "path dependency" of new energy sources such as PV and wind.

The traditional energy system of China is vast, which means that deep decarbonization of the energy sector cannot be achieved overnight. In fact, China has the largest and fastest-growing coal power infrastructure in the world, making it challenging to phase out coal fast enough to achieve net zero emissions within a few decades. Taking the lifetime of coal-fired power plants into account, the earliest full phase-out of conventional coal-fired power plants is 2045 [95].

According to the "Opinions of the Central Committee of the Communist Party of China & State Council of China on the Complete and Accurate Implementation of the New Development Concept for Carbon Peak and Carbon Neutrality", China has chosen to depend heavily on PV and wind for its new energy development (Table 4). Studies show that the Chinese PV industry has grown exponentially over the past two decades and it is the largest solar installation country in the world [96]. China already has a group of world-class PV and wind companies, and PV and wind generation has entered the era of grid parity and is no longer a subsidy-driven new energy resource. Globally, the potential to obtain energy from PV on the same land far exceeds that of bioenergy crops [97], which is negative for anaerobic co-digestion [8]. At present, the cost of electricity generation from biogas technology remains prohibitive, with the levelized cost of energy for biogas production almost double the levelized cost of energy for PV and wind. It is foreseeable that the opportunity to release the commercial value of biomass will only be realized once the maximum commercial value of photovoltaic and wind energy has been achieved.

Table 4. China's low-carbon strategy non-fossil energy goals.

Year	Proportion of Non-Fossil Energy Consumption	Total Installed Capacity of Wind and PV Power
2022		679 GW
2025	20%	>1200 GW
2030	25%	
2060	>80%	

Source: [98,99].

With overemphasis on the energy value of biogas technology for investors, when the energy benefits of biogas are premature, actors are attracted to the industry by the expectation of energy value, but when the expectations are not met, they become disillusioned with biogas technology or even do not consider it ever again [94], which is detrimental to biogas development.

5.1.3. Establish Expectations for Multi-Functional Biogas Technology

The Chinese central government has recognized the importance of the multi-functional characteristics of biogas technology. According to the "14th Five-Year Renewable Energy Development Plan", the positioning of biomass energy is a diversified development, namely the multi-functional mode of biogas as defined in this paper, and in the "Implementation Opinions on Accelerating the Transformation and Development of Rural Energy to Help Rural Revitalization", three modes of biogas utilization are given, which is actually the multi-functional application of biogas.

(a) Big Cycle: Regional organic waste centralized treatment to produce biogas, bio-natural gas projects

In counties with large-scale livestock farming, combined with rural organic waste management, the construction of regional organic waste centralized treatment projects to generate energy.

(b) Medium Cycle: Agri-park-style "breeding–biogas–planting" projects

The biogas project is used as a link to combine breeding and planting in a circular agricultural park, generating energy for the park's own use.

(c) Small Cycle: farm-style biogas projects

Farmers can use biogas in their yards as a link to organic farming, as well as the "pig–biogas–fruit" recycling model with anaerobic digestion for households.

The Big Cycle is similar to the M_{ABC} model, but this cycle involves too many stakeholders, especially because the collection of organic waste in rural areas is extremely difficult, there are residue elimination challenges and high technical barriers to the purification of bio-natural gas, and the economic efficiency is unclear. Due to its positioning as a centralized treatment project for organic waste in an area, it can be regarded as a category of investment in rural infrastructure construction and as a government project for people's livelihood and environmental protection. The Medium Cycle is a typical M_{ABC} model that faces the challenges of inadequate regime pressure on each function at present., Focusing on resolving the coupling relationship between cultivation and breeding, it could become a specific biogas multi-functional model that is easier to implement and replicate. The Small Cycle is one of the M_{AB} models and could be considered as a new position for China's remaining 30 million households biogas digesters, with less emphasis on energy use and more on environmental management and agriculture.

Most of the biogas industry in China is manure-based systems, with more than 90% of the feedstock being livestock manure (Figure 3). The most important need for biogas projects in China, regardless of scale, is not the production of biogas, but the treatment of waste and as much prevention of secondary pollution as possible. Therefore, the non-energy value provided by anaerobic digestion far exceeds the energy recovery value [12].

Since 2015, the Chinese government has launched a series of projects for the resource recovery of livestock and poultry manure, such as a demonstration project for the resource recovery of livestock and poultry breeding waste for the whole county, and a project for the introduction of organic fertilizers instead of chemical fertilizers for fruits, vegetables, and tea. The nutrient recovery system tends to be normative. Therefore, the land use of the digestate must be the expected focus of biogas technology in China at this stage.

5.2. Insights from the Biogas Industry Transition Pathway

5.2.1. Transition Takes Time and Trust

Both energy [100] and agricultural transitions [101] are long and slow. According to the law of energy technology deployment, when technologies are new, they experience exponential growth over decades [102]. History shows that it takes decades, maybe even more than a century, to move from technological innovation to niche and then to dominance [103,104]. At the same time, the net zero 2050 goal is a huge cost, and arguably, only the U.S. and a few wealthy countries could bear the enormous net zero transition cost [105]. Based on the China-TIMES-MCA structure, to control the energy transition, the cost of bioenergy means it will not be able to be deployed on a large scale until after 2040 [7], which means that the energy attributes of biogas technology will be less urgent in China.

Chinese biogas sector stakeholders are coping with the indisputable fact that the biogas transformation is difficult and long. Taking Chinese energy security and climate change ambitions into account, stakeholders need to be confident that there will be a place for this versatile technology in China. As in Stockdale's paradox [106], no matter how brutal the current situation is, the faith in winning in the end must be maintained.

5.2.2. Incremental Is Better Than Radical Innovation

The agricultural sector tends to be risk-averse and expects mature technologies, models, and markets. Most Chinese agricultural stakeholders expect the central government to promote proven and effective technologies with significant economic benefits. If policymakers adopt a radical innovation strategy at an inopportune moment, many projects will collapse, even if a few demonstration projects survive, as has been the case in China's biogas industry over the past two decades. This process will inevitably generate negative emotions among agricultural stakeholders, shake the confidence of policymakers, and lead to changes in policy support for medium- and long-term agendas. Worse, the persistent resistance can extend to the point of technological substitution.

Biomass utilization remains at the level of niche experiments [107]. Germany, recognized as the most advanced country in the biogas industry, is still trying to find a more profitable biogas application model [83]. On the other hand, German farmers need policies to support biogas production [108]. Therefore, the transition of the biogas industry at this stage must be cautious enough.

Incremental innovation may seem conservative, but it is not a negative approach. History is littered with technologies that matured too early, failed to adapt to the industry, and ultimately failed. Rather than expanding technologies and industries prematurely, the early experimentation and learning phase is a more logical way to transition [104]. Numerous studies have shown that modest niche innovations are more likely to succeed, and that a patchwork approach to biogas development is more successful than a breakthrough approach [64].

In addition, the International Energy Agency has emphasized for many years that current investments in the global energy sector are insufficient to meet both near-term energy needs and long-term transition goals [109]. Similarly, given the urgency of the energy transition, the Chinese government will strive to financially support the relatively mature new energy industry. According to the "Notice of the State Council on the Issuance of the Action Plan for Carbon Peaking by 2030", published in 2022, intensive investment strategies in the biogas industry are unlikely before 2030. After 2030, the Chinese biogas industry will enter a period of radical innovation, but a "window of opportunity" is still needed.

5.2.3. Consistent Political Support Is a Guarantee for Transition

The lifespan of biogas systems is 15–20 years [110,111], while the risks are significant. As social technology evolves, biogas projects are often maintained, upgraded, renovated, or even dismantled, which may require more investment than the complete replacement of new technologies. It is not practical to operate biogas projects without policy support for stakeholders.

Ambitious but short-lived "big buck" or erratic "go-and-stop" policy initiatives are not suitable to trigger a long-term energy transition; the "impatience" of innovation is detrimental when it comes to stimulating innovation and the deployment of new energy technologies in niche markets [104]. Only stable and consistent policies have a catalytic effect on biogas production [75]. Dynamic policies are also needed for the German EEG agenda. The Danish biogas development history concludes that biogas technology has developed along discontinuous, non-linear lines, and the only way to success is to constantly adapt to the problems with existing technologies [112]; therefore, dynamic policy adjustment is also a guarantee for the biogas transition.

Chinese biogas transition requires planning, with the long-term goal of achieving full-function biogas applications, the medium-term goal of achieving multi-function coexistence, and the short-term goal of achieving the most market-appropriate multi-function model. This study suggests that China should support limited biogas pilot projects and achieve breakthroughs in key biogas technologies before 2030. From 2030 to 2050, a significant number of pilots will be conducted with a declining post-subsidy policy with sufficient funding and regime pressure. From 2050 to 2060, widespread dissemination of socio-technically feasible biogas projects is the preferred transition strategy.

5.3. Implications of China's Sustainable Biogas Transition for Basic Research

Establishing sustainable biogas-coupled agroecosystems is an ultimate goal in China. The current research focus on anaerobic digestion for biogas production requires a balance between waste management and nutrient recovery, considering that both the demand for renewable energy and climate change will put pressure on China's biogas transition. This research proposed the following suggestions for basic biogas research.

Research should focus on the effective removal and risk assessment of pollutants in biogas technology, including but not limited to chemical oxygen demand, antibiotics, resistance genes, heavy metals, heavy metal resistance genes, microplastics, and emerging pollutants. It should be noted that not all pollutants are suitable for simple removal or degradation; the impact of anaerobic processes on plants, soil, the environment, and humans must be assessed.

Regarding nutrient recycling, stakeholders need to distinguish between different application scenarios of biogas models for research. In the environmentally friendly biogas scenario, it is necessary to maximize the efficiency of nitrogen and phosphorus removal under the premise of efficient gas production. In the case of biogas-associated agroecosystems, the efficacy of different biogas models for nutrient recovery must be considered, such as the efficacy of biochar-added biogas systems for nitrogen and phosphorus recovery. Dry fermentation, and manure concentration–separation will also be popular areas to reduce manure discharge.

Basic research on more efficient energy recovery remains desirable, but the experimental design needs to be more contextualized to the realities of China. For manure straw co-digestion, the raw material in China can only be dry yellow straw, and cannot follow the silage commonly used in Europe; such technology will create controversy in China about food security.

Using tools such as life cycle assessment to study emission reductions in different models, biogas plant-based carbon capture, utilization, and storage, and methodologies for accounting for carbon emissions from agricultural sources will be the hot spots for research into low-carbon strategies. Coupling techno-economic analysis and life cycle assessment to ensure sustainable production systems could also be a hot spot.

6. Conclusions

By 2030, China will have to abandon expectations for energy production from manure-based biogas. Resource utilization and waste management are needed as investment expectations to ensure the survival of the biogas niche market in China.

The transition is time-consuming, so it is crucial to be confident that biogas can be a significant renewable energy source by 2060. Radical niche innovation is not encouraged, which will both increase the cost of the transition and erode stakeholder confidence. Haste makes waste.

As expectations for biogas technology change over time, a dynamic strategy is needed. On the other hand, a robust long-term policy can ensure continued support for biogas niche experimentation and the incubation of these niche innovation markets.

The transition of the biogas industry requires a broader coalition and closer links between basic research and industrial applications.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/su15065299/s1, Table S1: Emission Reduction and Economy under Different Strategies.

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Abbreviations

PV, photovoltaic; SNM, strategic niche management; NIMBY, not in my back yard; A, waste management; B, nutrient recycling; C, energy recovery; D, climate benefits; M_{AB}, model A, B multi-functional; M_{ABC}, model A, B, C multi-functional; M_{ABCD}, model A, B, C, D multi-functional; Mt, million tons; CO_2e, carbon dioxide equivalent; CNY, Chinese yuan renminbi; RS, report scenario; RI, radical innovation; II, incremental innovation; MW, megawatt; GW, gigawatt; EEG, German Renewable Energy Sources Act.

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