Progress and industrialization development trends of the anaerobic digestion technologies for bio-natural gas

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Abstract: The production of bio-natural gas through anaerobic digestion not only realize the resource utilization and harmless treatment of urban and rural organic wastes, but also reduce the emission of methane and carbon dioxide. However, as an independently industry, bio-natural gas has some prominent challenges compared to household biogas and small-scale biogas projects. For the healthy development of the bio-natural gas industry, system analysis and planning have become particularly important. This study reviews the current development status of the bio-natural gas industry and innovatively analyzes the development direction of industry from a multidimensional perspective. Leading opinions are provided based on system analysis. Three major technological breakthroughs that have supported the success of regional bio-natural gas industry are revealed. The completeness of industrial technology, the objectivity of industrial regional development and the inevitability of the comprehensive benefits of the industrial chain are the major development direction of the bio-natural gas. Finally, according to the three major demands of new energy fuel, electricity and energy storage, two new energy systems based on bio-natural gas and the synergistic development of multiple new energy sources are proposed. This study provides theoretical and practical guidance for the bio-natural gas industry.

Keywords: bio-natural gas, anaerobic digestion, technological progress, industrialization, sustainable development
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1 Introduction

In recent years, the quantity of organic wastes in urban and rural areas, such as straw, livestock manure, household wastes, and kitchen wastes has increased rapidly. It may cause serious environmental pollution if those wastes do not obtain effectively treated[1]. Anaerobic digestion (AD) technology can effectively recover and utilize biomass energy, reduce energy consumption, environmental pollution, and greenhouse gas emissions[2]. Using AD to produce biogas is a significant method that combines environmental protection with renewable energy development. AD technology has received widespread attention from countries around the world[3].

Biogas is produced from the degradation of organic wastes under the decomposition of anaerobic fermentation bacteria. It is discovered early and used as a cooking fuel[4]. The household digester is mainly used for wastes storage in the village and biogas is the byproduct. Small biogas station aims to realize reduction and harmlessness of wastes, which is still an affiliated industry of municipal treatment[5]. However, bio-natural gas is an independent industry and it aims to effectively produce bio-natural gas with low cost. Therefore, the environmental issues and economic benefit, which are ignored when it is a subsidiary industry, become very prominent.

The number of traditional household biogas digesters grew the fastest in 2008, with 13 600 new household biogas digesters added[6]. However, the growth rate slowed down after 2009. The number of scrapped household biogas digesters exceeded the number of newly added ones by 2016. This is the result of social development and a signal of the transformation and upgrading of the biogas industry. Since 2015, the government has shifted its focus to pilot large-scale biogas and biogas projects. By 2018, the number of large and medium-sized biogas projects had exceeded 18 000, with 65 pilot projects for bio-natural gas projects and a total tank capacity of 21.781 million m^3, which was 4.98 times the total tank capacity of 4.5148 million m^3 in 2008[7].

In terms of bio-natural gas (BNG) production potential, literature has shown[8] that the biogas produced from feces and straw can produce 63 billion m^3 of bio-natural gas annually. The Guiding Opinions on Promoting BNG Industrialization point out that from 2025 to 2030, China's BNG development goals are 10 to 20 billion m^3 per year, with huge development potential.

After years of technological innovation and industrial integration, AD biogas production projects have transformed and upgraded from small-scale biogas to regional bio-natural gas that deals with environmental issues and yield clean energy. The transition of biogas to bio-natural gas is like a small sampan upgrade to an aircraft carrier, which is shown in Figure 1.

As the BNG industry gained rapid development, some problems have become prominent, such as the collection and supply of raw materials for the full-load operation, high overall energy consumption, low economic benefits due to the low value-added of the product, difficulty in treating the tail water as well as social approval[9]. These problems were not emphasized in the biogas project when it was a subsidiary industry. However, those problems were difficult to deal with after it became an independent industry,

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which greatly influenced the healthy development of BNG. It is necessary to review the development status of BNG industry in China and other areas of the world and summarize the experience of industrial development. Problems in AD technology are organized, and suggestions are provided for the future development trend of the BNG industry based on the successful BNG industry demonstrations that have been achieved in China.

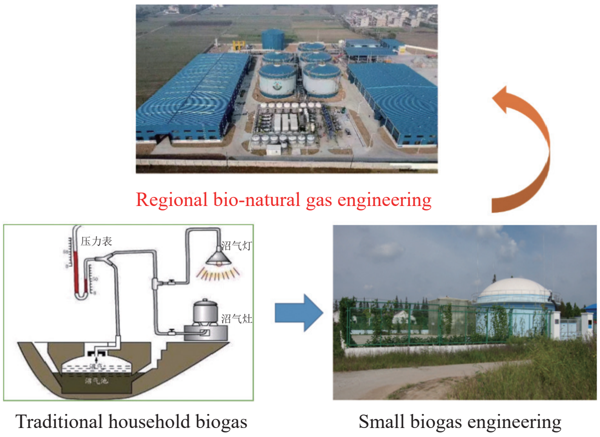

Figure 1 Revolutionary progress of traditional biogas to regional bio-natural gas

2 History and status of bio-natural gas

2.1 The development of bio-natural gas in China

The origin of biogas can be traced back to ancient China. The Han Dynasty's "Qi Min Yao Shu" recorded the method of using human manure and straw to produce biogas. The modern biogas engineering of China restarted since the 1970s with the high attention and strong support of the government[10], and the process of was divided into four stages. First stage, initiation, pilot and demonstration. Second stage, adjustment and consolidation. Third stage, rapid development. In the rapid progress of biogas engineering, some problem appeared. People usually pay high attention to the construction of biogas project while neglected the management segment, which resulted in the damage of biogas digester or low gas production efficiency. Fourth stage, equal attention to construction and management, transformation and upgrading. There was a total of 40.5771 million household biogas digesters and 100.9976 thousand biogas engineering stations within China by the end of 2017, with a stable gas production of over 2.6 billion m^3[6]. Combining with the construction of new rural areas and adapting to local conditions, the government encouraged enterprise to build centralized production and supply of bio-natural gas projects using crop straw and livestock manure as fermentation materials in rural areas with conditions. This measure can achieve standardization and serialization of engineering design and construction.

BNG has shifted from traditional small biogas facilities to regional bio-natural gas engineering due to the development of technology and the requirements of social benefits. The fields and technologies involved are expanding day by day, and large-scale bio-natural gas engineering is gradually becoming mainstream[7]. The main research hotspots for anaerobic fermentation technology in China are the utilization of straw resources, the utilization of livestock and poultry manure resources[11], the anaerobic synchronous fermentation technology of mixed materials[12], and the post-treatment technology of biogas residue and slurry. Insam et al.[13] comprehensively reviewed the beneficial effects and challenges that need to be addressed in the resource utilization of anaerobic fermentation sludge, including its impact on soil microorganisms[14], promotion of cycling of elements such as C, N, and P[15-17], heavy metals[18], organic pollutants[19], pathogens[20], and the risks of toxicity inhibitors[21].

From the perspective of policy, the government has attached great attention to the development of renewable energy, the treatment and utilization of agricultural wastes in recent years in China. The Renewable Energy Law of the People's Republic of China was passed on February 28, 2005, elevating the development and utilization of renewable energy to a strategic height of "increasing energy supply, improving energy structure, ensuring energy security, protecting the environment, and achieving sustainable economic and social development". In the process of national "14th Five Year Plan" layout construction and comprehensive promotion of rural revitalization strategy, the transformation and upgrading of the biogas industry is also constantly being explored and implemented. Especially when the government proposed to incorporate "carbon peak and carbon neutrality" into the overall layout of national ecological civilization construction, new situations and challenges emerged for the next development of bio-natural gas industry. The National Development and Reform Commission, the Ministry of Agriculture and Rural Affairs, the National Energy Administration and other departments formulated a series of short-term and medium to long-term development plans based on the current development status of the bio-natural gas industry and the national energy development demand. They made detailed planning and layout for the construction content, scale and quantity, utilization methods of biogas respectively, and provided corresponding subsidy standards and guarantee measures to systematically promote the development of BNG.

In 2015, the National Development and Reform Commission explicitly supported pilot projects with a daily output of over 10 000 m^3 of bio-natural gas, laying the foundation for the bio-natural gas industry[22]. In 2023, the issuance of the "Opinions of the Central Committee for Deepening Reform on Promoting the Gradual Shift" from Energy Consumption Dual Control to Carbon Emission Dual Control further enhanced the development space of the industry. The bio-natural gas project begun to transform and upgrade towards regional environmental management and the clean energy industry of BNG, which was related to rural revitalization, new energy, and the dual carbon national strategy[23].

2.2 Development history of biogas in the other regions around the world

The continuous consumption of fossil fuel has resulted in increasingly energy depletion and environmental pollution problem, which becomes an urgent task to explore high efficiency and stable renewable energy for many countries. The economic development models of various countries gradually transition to post carbon development models, but this process is influenced by various levels[24]. Gupta et al.[25] reviewed the history of human discovery and utilization of biogas. Among many renewable energy sources, biogas has a dual attribute: carbon reduction and sustainable energy[26]. European countries attach more importance to the development of biogas, and the biogas market is more mature than developing countries[27]. For developing countries, biogas mainly comes from small-scale biogas projects or household biogas digesters, and the biogas is used as fuel[28]. However, in developed countries, biogas mainly comes from large-scale biogas factories, and its value is upgraded by transform to electricity or bio-methane[29]. Brémond et al. conducted a comprehensive analysis of the biogas industry in Europe[30], and the data showed that Europe had 18 202 biogas plants and installed 12.6 GW in 2018, making it the world leader in biogas power generation. Among European countries, Germany was the leader in biogas production, with 9500 biogas plants. Power generation and purified to produce bio-methane are the two main paths for biogas appreciation. As the second largest biogas market in Europe, Italy mainly uses biogas industry to treat crop waste. Thanks to clear goals and successful policies, Italy has achieved large-scale production of biogas[31]. The biogas produced in Sweden is mainly used to produce bio-methane. As Sweden does not have a natural gas pipeline, bio-methane is used to provide fuel for vehicles in the form of compressed or liquefied state. Denmark injects bio-methane into the pipeline network and uses it for urban cogeneration systems with regional heating systems because it has a developed natural gas network. In France, the bio-methane industry has experienced rapid growth. But it may be challenged and restrained by the future energy policies, as the target for the proportion of bio-methane in total natural gas demand has been lowered. Chasnyk et al.[32] reviewed the development history of biogas in Poland and Ukraine, and found that agriculture accounted for a relatively large proportion of their economic sources, and the use of biogas as a substitute for traditional electricity had good prospects. Sweden produced approximately 2 TW·h of biogas in 2019, and the achievable potential for utilizing AD to produce biogas will be 7 TW·h by 2030[33].

In developing countries, although Brazil has abundant organic wastes resource and great potential for biogas production, the biogas market has only just begun due to the lag of biogas technology and government policies[34]. Bertolino et al.[35] compared and analyzed the biogas development models of Brazil and Italy from the perspectives of policy and energy inequality. The results indicated that compared to Brazil, Italy's regional spatial scale was more correlated. The biogas market in India developed relatively slowly, and the research of Singh et al.[36] showed that a significant portion of the population in India still relied on traditional biomass as a fuel for household cooking. Heidari-Maleni et al.[5] detailly analyzed the potential of biogas production in Iran. The results indicated that although Iran had great potential for biogas production, the development of the biogas industry was slow due to insufficient technology and lack of public awareness of biogas. Lohani et al.[4] analyzed the current situation of the biogas industry in Nepal and found that due to fluctuations in raw materials, temperature effects, and limitations in local technology, less than 1% of the total biogas potential had been utilized. Similarly, although Kenya has the potential for biogas in 1.3 million households, the development of the biogas industry in Kenya is slow due to a lack of policy support and technological development[26]. Nevzorova[37] studied the potential of biogas as a renewable energy source from the perspective of space and technological innovation, and the results showed that Russia didn't have a demand for biogas, but it can be exported to European countries. In a conclusion, the comparisons about the bio-natural gas technology between China and other countries are listed in Table 1.

3 Progress in bio-natural gas technology and industry challenges

Many challenges of bio-natural gas industry become apparent. Previously, the amount of raw materials relied on the main system.

Table 1 Comparisons about the bio-natural gas technology between China and other countries

	Advantages	Disadvantages
China	Large installed capacity, high potential and wide social benefits[8]	Late start, incomplete technical system and lagging behind in R&D
Germany	Leader of the industry, advanced technology, high conversion efficiency and output	High dependency for electricity price subsidy and high transportation costs[38]
Italy	Clear goals and successful policies, diversified incentive systems	Energy infrastructures need to be strengthened, low coordination of energy systems[39]
France	Rapid growth	Restrained by future energy policies
Denmark	Developed natural gas network	High production cost[40]
Brazil	Abundant organic wastes resource and great potential	Lag of technology and government policies
India	Rich biogas resources	Biogas development relatively slowly
Iran	Great potential for biogas production	Insufficient technology and lack of public awareness of biogas

The clean energy was byproduct when it was subsidiary industry while now it is the guarantee of project income. What we need to consider are how to ensure the full load of bio-natural gas production. Therefore, high efficiency AD technology should be further investigated. In addition, the energy consumption of digester was ignored before, while that of the bio-natural gas industry is enormous. The residue of household biogas or small biogas could be directly used as fertilizer because the amount of it is small, while that of the bio-natural industry is extensive. Thus, the residue of bio-natural gas needs to be processed to match the demand. Challenges for bio-natural gas come from shifting goals and industry models. It is because of these challenges that the rate of industrial expansion of bio-natural gas has been hampered from 2017 to the present, especially in China where the industry volume has largely not increased. In conclusion, continuous technological innovation is necessary to promote the sustainable and healthy development of the industry.

3.1 The dilemma of fermentation with multiple raw materials

The gas production efficiency is limited as the AD raw materials are diverse. Because the efficient bacterial strains for each raw material and metabolic pathway selection are different[41]. AD can be divided into three stages and each stage has a distinct microbial community. The best way to increase gas production is screening suitable strains[42]. The limiting factors for low bioconversion rate mainly include lignocellulose, inhibition of sludge layer, ammonia inhibition, temperature and pH value, etc. These factors greatly hinder the conversion of biomass into biogas, and many scholars have conducted detailed research on this topic.

3.1.1 Lignocellulose

Lignocellulose is a natural high molecular weight organic compound widely present in biological residues, with potential energy and material utilization value. However, the low reaction rate of lignin during the hydrolysis process has become one of the main bottlenecks in anaerobic digestion[43]. The research of Ibro et al.[44] showed that lignocellulosic raw materials were still a sustainable choice although lignin had stubborn and anti-degradation properties. Xie et al.[45] used maize stover as an example to study and reflect on the key challenge in AD. Straw becomed stubborn due to its complex structure and diverse cell wall composition. Therefore, efficient pretreatment methods were needed to open complex cell structures, promote subsequent enzymatic hydrolysis of cellulose, and achieve high value-added utilization of maize stover. Mirmohamadsadeghi et al.[46] reviewed the influencing mechanisms of different pretreatment methods on microbial diversity. Results showed that pretreatment significantly affected the production of biogas. Donkor et al.[47] discussed the effect of alkali pre-treatment by bioaugmentation on lignocellulose. Results showed that the integrated system realized 90% biodegradability and 47% CH_4 production increment. Jin et al.[48] investigated the performance of enzymatic pretreatment in wheat straw anaerobic digestion. Results showed that the degradation of cellulose was 37.47% and the production of biogas increased. Dahunsi[49] investigated the effect of mechanical pretreatment on different lignocellulosic biomass. Results showed that mechanical pretreatments increased the production of biogas by 22% and reduced the reaction time. Bittencourt et al.[50] investigated the effect of advanced oxidative pretreatments on sugarcane bagasse. Results showed that cascade pretreatment method improved lignin removal efficiency. Xu et al.[51] discovered that the stubborn and anti-degradation properties of lignocellulose were one of the key factors limiting hydrolysis during anaerobic digestion. Lignocellulose biomass is mainly composed of cellulose, hemicellulose, and lignin. The chemical composition and structural factors of these components play an important role in the hydrolysis and decomposition of substrates. By removing some cell wall components, the accessible surface area of substrates can be increased, which improves surface availability.

3.1.2 Scum layer suppression

During the AD process, the scum in the top of fermentation tank will accumulate and develop into scum layer, which will reduce the hydraulic retention time, inhibit the production of biogas, and be detrimental to the AD process[52]. Hao[53] discovered that the special structure of maize straw made it difficult to absorb water during the AD process, resulting in low settling ability. Besides, the release of biogas caused the dehydration and crust of scum. Once the scum layer crusts, it can lead to failure of AD, which has become a bottleneck problem. Pan et al[54]. developed a novel digester which could control the formation of scum layer. Results showed that the novel digester improved the production of biogas up to 116.%. On the other side, the scum contains various organic matter and has the potential to produce biodiesel[55]. Bi et al.[56] exploited a new technology that transformed the scum into biodiesel. Results showed that 70% scum could be converted to biodiesel. Anderson et al.[57] investigated the conversion of scum to biodiesel through hydrolysis and solvent extraction. Results showed that zinc-based catalyst improved the reaction speed while as well as increased the cost.

3.1.3 Ammonia inhibition

Ammonia inhibition has a significant impact on the microbial activity and community during anaerobic fermentation of poultry and livestock manure[58]. Xu et al.[59] pointed out that ionized ammonia in the environment inhibited methane synthase, and free ammonia quickly diffused between cells, causing K^+ imbalance and greatly affecting the activity of methane producing microorganisms. Fu et al.[60] found that the mass concentration of ammonia exceeding the inhibition threshold had a negative impact on the efficiency of the methane production step. Compared with other anaerobic microorganisms, methane producing bacteria were more sensitive to ammonia because their cell walls lack peptidoglycans and had a weak structure. Therefore, ammonia inhibition can reduce methane production efficiency and even lead to anaerobic fermentation failure. Yellezuome et al.[61] reviewed the effect of ammonia stripping technology on the abatement in ammonia inhibition during AD process and result showed that the efficiency of ammonia stripping was determined by the pH of raw material. Lv et al.[62] tested the performance of using isotope to monitor ammonia inhibition. Results showed that novel isotope realized pre-warned of process failure.

3.1.4 Temperature and pH value

The activity and metabolic rate of microorganisms may change at different temperatures and pH value, thereby affecting the stability and efficiency of the fermentation process[63]. If the temperature is too high, microorganisms may be damaged or even die, leading to fermentation failure. However, if the temperature is too low, the metabolic rate and activity of microorganisms may decrease to an extremely low level, leading to the inability of fermentation to proceed. To solve the problem of single product and low efficiency in the current agricultural wastes resource utilization, Ren et al.[64] used pig manure and Ganoderma lucidum mushroom bran as raw materials. The anaerobic co-fermentation process of pig manure and mushroom bran was studied under different pH values to investigate the acid production law and microbial community structure changes of the two anaerobic fermentation processes. The effect of different temperature (20°C, 32°C, 37°C and 55°C) on AD process with the vegetable waste and swine manure as material was conducted by Ren et al.[65]. Result showed that 32°C was the optimal temperature for vegetable waste and swine manure co-digestion. Zhao et al.[66] tested the effect of temperature on the digestion of pretreated maize stover. Result showed that mesophilic condition is the potential method to treat pretreated maize stover. Zheng et al.[67] conducted an experiment to solve the low bioconversion efficiency of AD in the winter. Result showed that the production of enzyme production was optimal when the temperature and pH were 16°C and 8.2, respectively. Tong et al.[63] investigated the effect of pH value on two-phase AD. Result showed that the production of methane improved when the ratio of acidification was 2:1.

3.2 High overall energy consumption

Anaerobic fermentation with multiple raw materials leads to the complexity of the fermentation process. The efficiency of AD may be significantly reduced if the macromolecular organic matter enters the fermentation tank without pretreated. Therefore, raw material pre-processing sessions are necessary. Physical, mechanical, thermal, chemical, biological and other pre-treatment methods increase the decomposition capacity of the substrate, thus increasing biogas production[68]. Among numerous pre-treatment technologies, mechanical crushing and pyrolysis are widely used in commercial applications because of their simple operation and mature technology. However, whether it is mechanical crushing or high-temperature pyrolysis, the energy consumption is enormous[69]. In addition, the anaerobic tank always needs to be kept at a medium temperature (38°C-45°C) during AD to keep that optimal temperatures for the methanogenic bacterial lineage to work efficiently. Therefore, the overall energy consumption of biogas production should not be neglected, and how to reduce the energy consumption while efficiently recycle the process waste heat is one of the challenges that need to be solved in future biogas projects.

Karimipour et al.[70] investigated the use of twin-screw extrusion mechanically for the pretreatment of lignocellulose, a macromolecular material from forestry bioresources. The results indicated that for every 1kg of lignocellulose processed, 2 kW·h of energy was required, and optimizing the screw structure significantly reduced energy consumption. Luo et al.[71] found that using low-temperature thermophysical pretreatment techniques at 100°C and 130°C had similar pretreatment effects. The pretreatment increased biogas fermentation efficiency and total slurry net power generation. Qian et al.[72] demonstrated that the optimal conditions for hydrothermal pretreatment were an initial water content of 55%, a pre-soaking time of 2 h, and a heat treatment time of 6 h. This condition increased the gas production rate and promoted the degradation and dissolution of cellulose and hemicellulose. Meng et al.[73] investigated a novel method for biogas purification. Result showed that ionic liquids could improve the purification efficiency and reduce the energy consumption. Khan et al.[74] optimized the upgrading process of biogas to reduce the energy consumption. Result showed that the specific energy consumption decreased by 15.4% after optimization. The research of Mahmoodi-Eshkaftaki and Houshyar[75] showed that biogas recirculation could reduce the energy consumption of AD.

Another reason for the high overall energy consumption is that the output of traditional biogas projects is limited, and a large part of the energy is not effectively utilized. For example, straw, the raw material for fermentation, is currently crushed in an immature process, which does not allow for effective screening of straw particles according to particle size. Straw pellets with moderate particle size can be completely used as high-quality fertilizer, and preferentially supplied to farms as livestock feed. The remaining low-quality straw pellets are used for AD to maximize the economic benefits. Besides, the biogas residue after solid-liquid separation is often regarded as wastes and requires a large amount of land for landfill, which increases operating costs. Biogas residue contains rich organic and inorganic nutrients and can be developed into organic fertilizer, which can not only increase project income but also help farmers reduce the use of chemical fertilizers.

3.3 Difficulty in tail water treatment

Biogas slurry is the tail water mixture after solid-liquid separation of anaerobic fermentation tank residues, which is rich in nutrients such as N, P, and amino acids[76], as well as toxic substances such as heavy metals[77], antibiotics, and plant inhibitors[78]. The tail water of biogas slurry can easily lead to the risk of secondary environmental pollution[79], and how to effectively deal with it is one of the challenges in biogas engineering. On the other hand, slurry and residues from AD contains multiple nutrients and it has high potential to become an organic fertilizer[80]. Nutrient recovery and harmless treatment of biogas slurry are key to achieving standard discharge and safe use in farmland[81]. Research has shown that the slurry of biogas can be used to produce biofuels by microalgae[82]. Li et al.[83] investigated a strategy that used biogas slurry to cultivate microalgae and produce biofuels. Results showed that adding appropriate amounts of nutrients to biogas slurry could reduce toxic substances and increase product quality.

In summary, this study has reviewed the main challenges faced by anaerobic fermentation, indicating the necessity of continuous innovation for the sustainable development of the biogas industry. The problems faced by the biogas industry vary from country to country due to geographic and policy differences. Therefore, the development of efficient anaerobic fermentation technologies and appropriate development strategies are adapted to the local context. A typical case study of a biogas project in Funan, Anhui Province, China, is presented below.

4 Typical case study of industrialized application of biogas

Traditional biogas cannot be integrated into the larger energy system due to low efficiency of gas production caused by small scale and unstable security of feedstock from a single source. To realize the effective substitution of biogas for traditional energy sources, it is necessary to develop large-scale biogas projects to ensure the integration and development of biogas with traditional natural gas. Since the 13th Five Year Plan period, with the support of the National Development and Reform Commission and the Ministry of Agriculture and Rural Affairs, China has carried out demonstrations of the biogas industry. Among them, the Public-Private-Partnership (PPP) project for the development and utilization of agricultural wastes biogas and bio-natural gas in Funan County, Anhui Province, adopts a comprehensive station field treatment approach for urban and rural diverse wastes, creating an overall development model for the county's BNG industry. Eight BNG production stations, a 270 km medium pressure gas transmission and distribution network, and a central liquid natural gas (LNG) peak shaving gas source station are constructed throughout the county, as shown in Figure 2. The project supplies 50 million m^3 BNG annually, and it is referred to by the Ministry of Agriculture and Rural Affairs as the "Funan model" for BNG.

Figure 2 The layout diagram of '8+1' station in Funan county

In 2022, the National Energy Administration released the "14th Five-Year Plan" for renewable energy, clearly pointing out that the future development of biogas in accordance with the county to promote the "Funan model" as a sample of policy development. Regionalization is of great significance in promoting the scale of the biogas industry, promoting green, low-carbon and recycling development, and comprehensively promoting rural revitalization.

The successful operation of the Funan project is attributed to several core technology innovations and breakthroughs.

1) To treat the problems of low bioconversion rate and large changes in mixed fermentation of diversified materials, the mechanism of synergistic mixing of diversified organic wastes and the technology of synchronous fermentation of woody fibrous and pulpy organic wastes are revealed. The fluid-solid drag models were established[84]. Thus, the gas production rate of multiple raw materials was improved. Bio-electrochemical systems such as double electrode plates were developed[85,86], which improved the gas production efficiency (from 30% to more than 65%) of difficult-to-degrade biomass in mesophilic anaerobic fermentation. In addition, breakthroughs in low-temperature anaerobic fermentation for biogas production and hydrogen-to-methane technology were established[87]. In terms of mixing technology, a mixed fermentation non-Newtonian fluid model with flow field optimization mixing technology was developed[84], which reduced the energy consumption of engineering mixing.

2) Aiming at the high energy consumption of heating in the thermal management of biogas engineering, the team constructed a physical-mathematical model of the heat load of biogas engineering, and for the first time, pioneered the application of heat pump technology in biogas engineering, which reduced the energy

consumption of heating. Based on the hot and cold hedge technology, a new energy management strategy was developed to improve the efficiency of site cogeneration and realize the comprehensive energy efficiency improvement[88]. A new cold energy recovery technology for LNG liquefaction energy storage was developed to achieve optimal energy allocation under dual peaking of gas and electricity[89].

3) In response to the difficulties in agricultural consumption and high transportation costs caused by the large amount of biogas slurry produced by anaerobic fermentation, research had been carried out on the preparation of biogas slurry organic fertilizer, nutrient recovery from biogas slurry, and development of new functional materials[90]. A chemical sedimentation-pressure-electrically driven membrane mass grading process was developed to realize the separation and recovery of organic-inorganic nutrients from the digestate and to obtain Nano-calcium carbonate[91,92].

5 Development trend of bio-natural gas industry

Based on a review of the BNG industry and typical case experiences, this study proposes three major technological progress trends in China's BNG industry: industrial technology completeness, emphasis on regional development, and attention to the comprehensive benefits of the entire industry chain.

China has many AD projects for organic wastes (referring to large-scale biogas projects) compared to Germany, but the production capacity is much lower than Germany. Firstly, there are significant regional climate differences in China. The scenarios of organic wastes are diverse, and the problem of industry shortage and blockchain is serious, which is an important factor that makes it difficult to effectively utilize production capacity. Secondly, in the 1970s, Europe began to promote biogas industrialization with a high industrial foundation. In China, however, biogas started with household biogas, which was simplified according to basic needs. And it began to achieve industrialization until 2015. Thirdly, because the project has not gone through long-term operation practice, the technical readiness is low and the technical progressiveness has not been effectively brought into play. Therefore, we must continue to innovate in technology, especially through in-depth theoretical research, to promote sustainable and healthy development of the industry.

5.1 Trend one: completeness of industrial technology

From a single focus on anaerobic technology to a multi-dimensional controllable technology system, the completeness of industrial technology includes multi-source organic wastes mixed collaborative fermentation, reliable engineering thermal efficiency, multi gradient comprehensive energy utilization and carbon reduction of gas and electricity, resource utilization of biogas slurry and environmental risk prevention, scientific planning of regional site layout, digitalization and intelligence of biogas production and supply linkage. A complete technical system is shown in Figure 3, and a schematic diagram of station field layout is shown in Figure 4. Industrial technology progress should not only break through the existing technical weakness, but also verify the completeness, matching and progressiveness of industrial technology through project demonstration.

5.2 Trend two: Regional development of the BNG industry has become an objective demand

The following difficulties push BNG industry to regionally develop: separation of planting and breeding, excessive manure in large-scale breeding farms, difficulty of residue directly returning to the field, inability to maintain simply meeting emission standards and cost in the breeding industry. The third-party treatment model for farm wastewater, which only collects solid manure, is not capable of eliminating environmental pollution. The disorganized manure roughly used for fertilization may even aggravate the predicament of regional disease prevention and control. The biggest challenge in the industrialization of new straw utilization is the seasonal imbalance of raw material supply and demand, which requires regional coordination and an organized straw broker model to undertake the responsibility of reliable collection of straw raw materials. The mode with single raw material and pure commercial activity can not solved the environmental governance dilemma, and government is unable to grant reliable revenue protection measures for these projects.

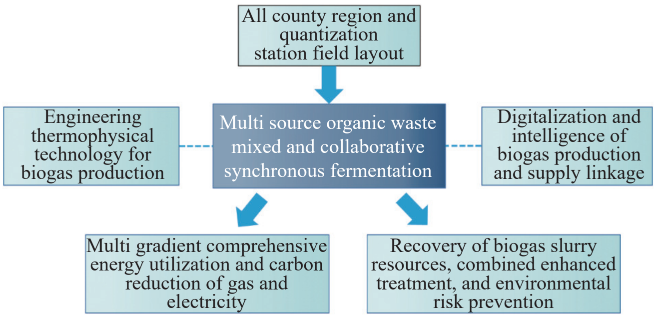

Figure 3 Multidimensional controllable technology system

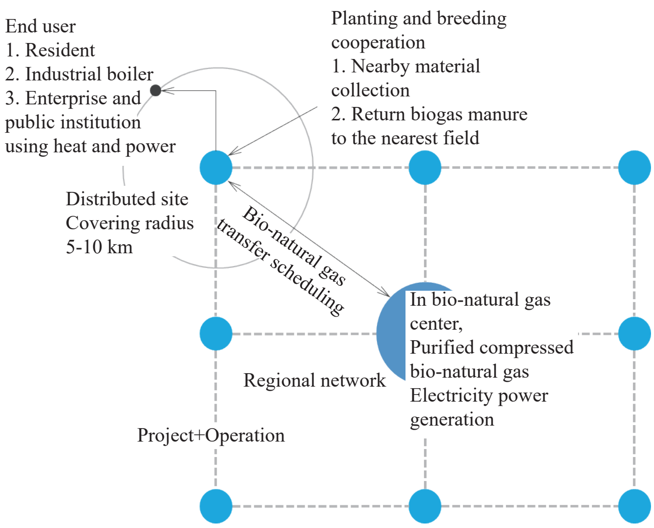

Figure 4 Schematic diagram of station field layout

5.3 Trend three: Focus on the comprehensive benefits of the entire BNG industry chain

From the perspective of the entire industry chain, all the waste (residential waste, planting waste, industrial organic waste, and aquaculture waste) are first collected and process from the raw material side. Then the organic fertilizer produced from those waste is determined whether returned to the field or not. Therefore, to solve the dilemma of living environment, it is necessary to focus on rural revitalization and county economic transformation, achieving reliable substitution of new energy, and reconstructing modern circular economy. These tasks cannot be fully completed by a single team, and it is necessary to have a large industry platform that coordinates industry and technology to go further. The layout of the entire industry chain is shown in Figure 5.

The expansion of industrial volume can support the soundness of the industrial chain. To realize the new energy as the core, circular economy and green economy co-development need to transfer from the single energy income path to entire industry chain. The ultimate problem of the BNG industry is the issue of revenue. In the past, we only focused on gas supply. Now, from the perspective of the entire industry chain, we can also consider environmental service fees such as aquaculture pollution treatment fees, government procurement services such as kitchen waste treatment fees, organic fertilizer sales, new material sales such as bird droppings, PHA, and degradable biomass material co production, green hydrogen and carbon trading. The industry may break through dependence on government subsidies and move towards industrial self-circulation from a single source of income to seven sources of income. The schematic diagram of industrial revenue sources is shown in Figure 6.

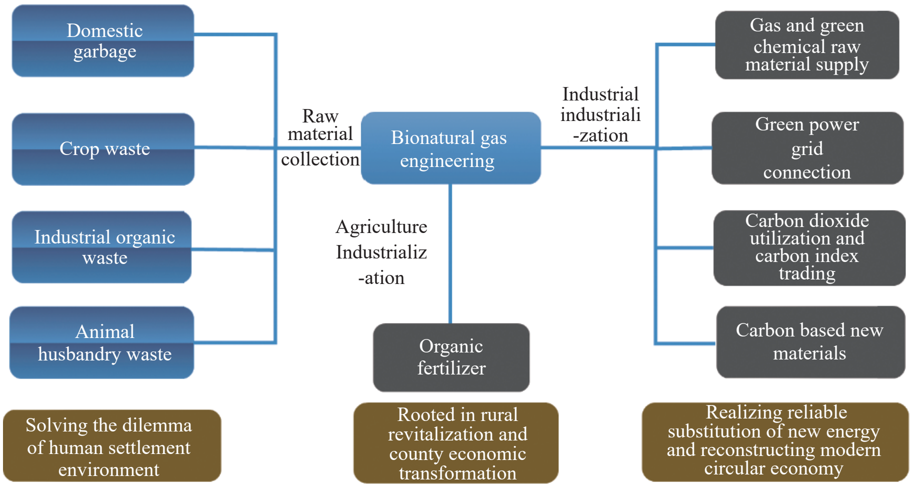

Figure 5 Schematic diagram of the layout of the entire industry chain

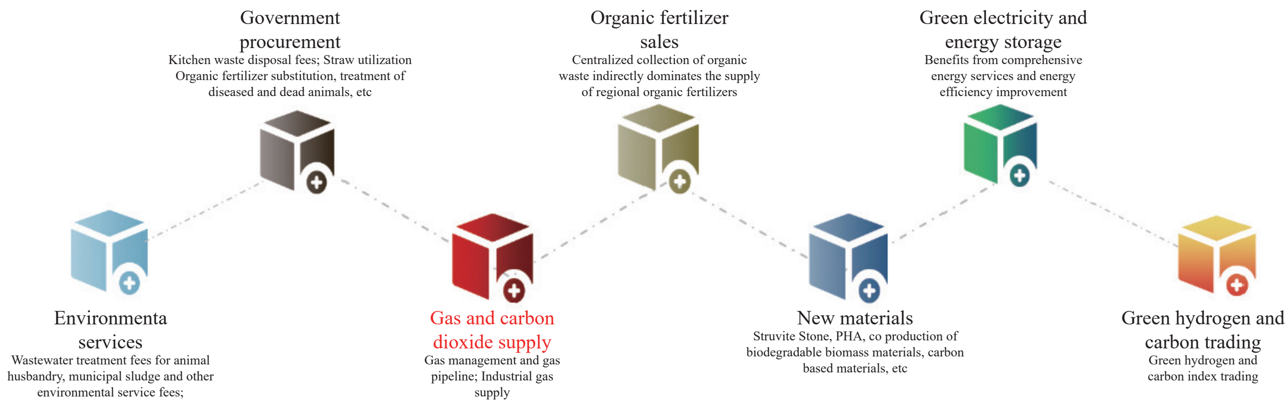

Figure 6 Schematic diagram of industrial revenue sources

5.4 Effect of technological advancements and industry trends on stakeholders

Technological advancements, regional and full industry chain will have significant influence on bio-natural gas industry and its relation industry. First of all, technological advancements may improve the treatment efficiency and the total quantity of raw material for the industry upstream. This will alleviate the pressure on farm effluent storage and improve the income of farmers, i.e. straw providers. On the other hand, the increase in sewage and straw treatment not only improves the utilization of resources, but also guarantees the implementation of the policy of 'Beautiful Country'. For the midstream of the industry, technological advancements and the development of full industry chain will drive the technological innovation of equipment manufacturers, expand the scale of the industry, enhance profitability, and accelerate the promotion of regional bio-natural gas across the country. For the downstream of the industry, the products of bio-natural gas industry include green fuels, organic fertilizers and functional materials, which greatly broaden the profitability of the industry. The increase of green fuel is conducive to energy saving and emission reduction in green shipping, green metallurgy industry. Organic fertilizers can reduce the use of chemical fertilizers and the damage to land. The development of functional materials such as low-cost hydrogen storage materials will promote the development of the hydrogen energy industry. In addition, the bio-natural gas industry is an important support for national rural revitalization, and the employment opportunities driven by the industry enable villagers to work at their doorstep and increase their income. The development and improvement of industries have also brought new economic growth points to the government. Overall, the technological advancements, the development of regionalization and full industry chain will be able to achieve a win-win situation for all participants.

6 Prospect

6.1 A new system of green electricity, green hydrogen production, transportation, storage and supply for biogas system

Renewable energy power generation has a serious phenomenon of abandoned wind, light and electricity. Energy storage will become the key to solving the efficiency and safety issues of the power grid caused by the large-scale integration of new energy into the grid[93].

The proportion of total power generation is still relatively low despite the rapid increase in the installed capacity of renewable energy power generation. One of the important reasons is that renewable energy generation, especially wind and solar power, exhibits significant seasonal and intraday variations, which are greatly affected by environmental factors and have a high frequency of fluctuations, greatly affecting the stability of the national power grid. As a result, wind and photovoltaic power output coefficients are low, and there is a serious phenomenon of wind, solar and power abandonment. The installed capacity and power generation of non-fossil fuels in China from 2015 to 2016 are listed in Table 2, and the output coefficients of different power generation methods in 2016 are shown in Figure 7. The comparison results indicate that theoretically, pyroelectricity can achieve a 100% output coefficient. The minimum output of coal-fired power plants is generally 40% to 50% of the rated capacity, which is insufficient for flexible response on the electricity side. However, the output of natural gas power plants can be quickly started and stopped to achieve large-scale peak shaving.

Table 2 Non-fossil energy installed capacity and power generation in China from 2015 to 2016.

	Unit	2015	2016
Power generation installed capacity			
Hydropower	MWe	31 954	33 207
Wind power	MWe	13 075	14 747
Solar power	MWe	4218	7631
Nuclear power	MWe	2717	3364
Other	MWe	9	7
Power generation			
Hydropower	Billion kW·h	11 127	11 748
Wind power	Billion kW·h	1856	2409
Solar power	Billion kW·h	395	665
Nuclear power	Billion kW·h	1714	2132
Other	Billion kW·h	1	1

To achieve the dual-carbon goal (Peak carbon emissions by 2030, and carbon neutrality by 2060), it is necessary to reduce the amount of electricity generated by thermal power generation and to reduce the consumption of primary energy sources such as coal. The share of renewable energy generation is expected to increase to 70% by 2060. The new idea of four element collaborative energy storage and peak shaving using BNG, cold, hot, and electrical provides a new perspective for regional energy regulation.

Energy storage technology includes chemical energy from chemicals such as methane and methanol, hydrogen production through electrolysis of water, compressed air, and thermal and cold storage. According to different energy storage durations, the current application scenarios of the main energy storage technologies are listed in Table 3. Combined with the characteristics of different energy storage technologies, a new idea of biogas cold, hot and electric quadratic synergistic energy storage and peak shifting is proposed. The first element: biogas itself is currently the only renewable energy source that exists in the form of chemical energy, and seasonal energy storage for solar energy can realize seasonal energy deployment, which is typical of ultra-long-term energy storage. The second element: the natural gas energy properties of biogas itself, combined with traditional natural gas, make it an important carrier for regional intraday gas electricity peak shaving, which is a typical long-term energy storage. The third element: relying on biological natural gas liquefaction energy storage, the cold and heat hedge to enhance the efficiency of the conversion of cold energy and electricity, providing a way out for the synergistic development of regional cold and heat integrated energy resources. The fourth element: hydrogen production through electrolysis of water and thus production of BNG, which already has the combined embodiment of short, long and ultra-long-term energy storage.

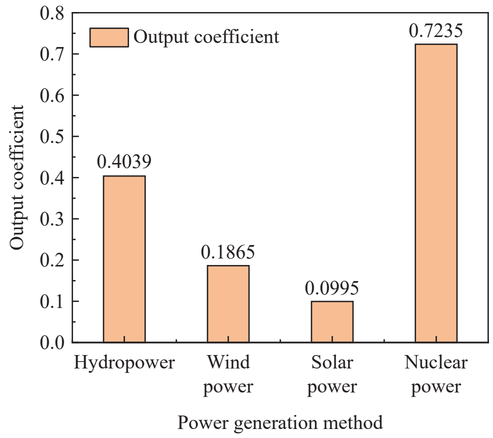

Figure 7 Output coefficient of different power generation methods in 2016

Table 3 The current application scenarios of the main energy storage technologies based on different energy storage durations

Type	Reserve type	Capacity based	Energy type	Power type
	Ultra-long	Long term	Short term	Instantaneous
Energy storage duration	Seasonal	4 h≤time≤1 week	1-2 h	15 min≤time≤30 min
Actual application scenarios	Strategic reserve or off grid energy storage	Peak shaving and valley filling or off grid energy storage	Composite energy storage scenario	Smoothing intermittent power fluctuations
Energy storage	•Chemical energy of chemicals such as methane and methanol •Water, salt, and phase change composite cold and hot energy storage •Mechanical potential energy of watershed reservoirs, etc.	•Pumped storage, com-pressed air, heat and cold storage, gravity energy storage, etc. •Lithium ion batteries, flow batteries, sodium ion batteries, etc.	•Lithium iron phosphate batteries, lead carbon batteries, etc. •water electrolysis	•Flywheel energy storage •Superconducting energy storage and supercapacitors •Various types of power type batteries (lead-acid batteries, cascade utilization batteries, etc.)

Overall, although BNG cannot achieve instantaneous energy storage, with the assistance of appropriate electrochemical batteries and based on the quaternary energy storage of biogas, it can provide a new perspective for regional energy regulation. Utilizing biogas combined with energy pipeline network, a system of new energy and green hydrogen production, transmission, storage and supply based on station-field type biogas industry can be established.

The main directions for hydrogen energy storage are: 1) Hydrogen production through electrolysis of water: the energy conversion efficiency is high, reaching 65% to 80%. 2) Bio-methane production: Under medium temperature conditions, 99% of H_2 is utilized by hydrogen producing methane producing bacteria, absorbing 69% of CO_2. After hydrogenation and purification, the methane content in biogas increases by 27.6%. Through this technology, future BNG can not only serve as a carrier of renewable energy, but also as a storage carrier for regional wind power and photovoltaics. 3) Steam reforming for hydrogen production: Yi et al.[94] had combined the technical characteristics of hydrogen storage and transportation and electrolysis for hydrogen production, as well as China's hydrogen transportation needs, and proposed that using hydrogen to extract gas from natural gas pipelines and reforming for hydrogen production could solve the problems of green hydrogen production and long-distance transportation. The methane steam reforming reaction is a reversible and strongly endothermic reaction, operating at high temperatures, with a hydrogen production efficiency of up to 70% to 90% through steam reforming.

A novel system of new energy and green hydrogen production, transmission, storage and supply based on station-field BNG industry can be established by utilizing BNG combined with energy pipeline network, as shown in Figure 8. Such integration realizes the effective coupling of the three green cycles: the H_2 cycle, the CO_2 cycle and the power cycle.

In terms of conversion efficiency, the conversion efficiency from methane to hydrogen is 70% to 90%, from green electricity to hydrogen is 49% to 53%, and the effective energy conversion rate for hydrogen liquefaction is 62% to 72%. Hydrogen to methane pipeline transportation is more reasonable and reliable than liquid hydrogen.

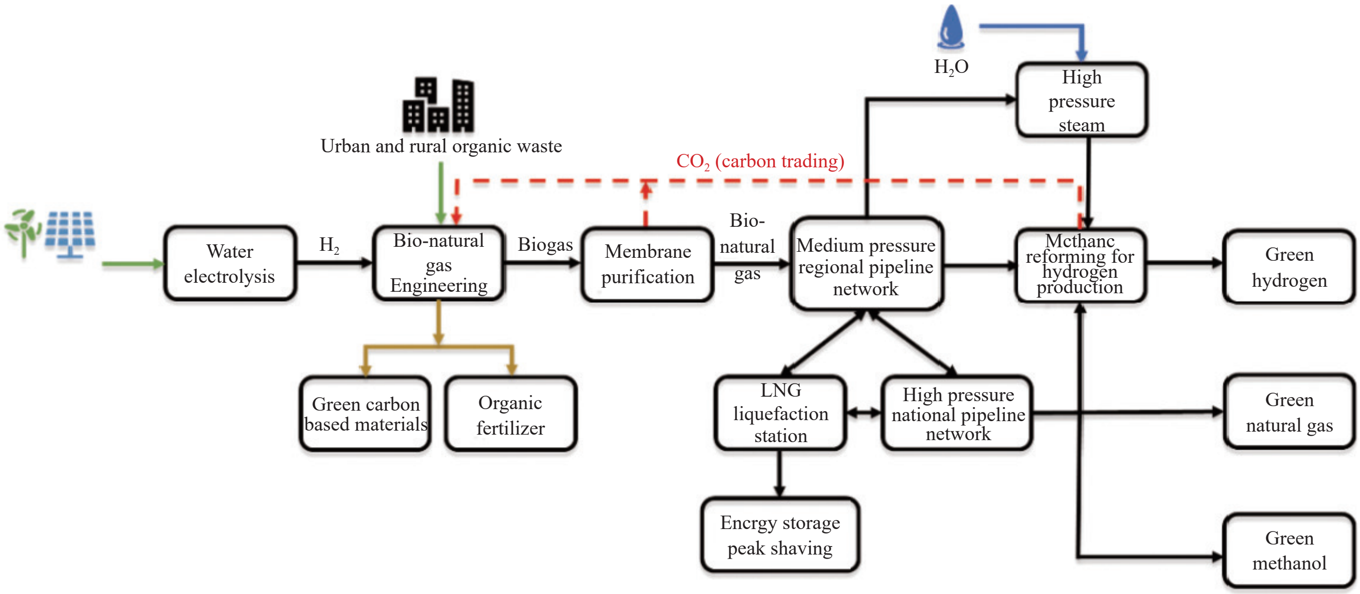

Figure 8 Hydrogen base, and carbon sink based on regional station field bio-natural gas industry

6.2 Gas-power dual-peak energy storage system based on regional biogas system

China's energy structure is shifting from one dominated by fossil energy to one that is cleaner and lower-carbon. The increase in the proportion of renewable energy promotes the sustainable and high-quality development of China's economy. However, the intermittent and fluctuating nature of renewable energy sources such as wind energy and solar energy has brought great impact on the power grid. The development of energy storage and peak shaving technology is the key to addressing the impact of new energy. At present, the most efficient energy storage system worldwide is pumped storage, but its construction and layout are limited due to geographical factors. BNG, as an important field of new energy, is developing towards regional integration. Due to the chemical properties of BNG, BNG projects can provide both green fuel and green electricity in a coordinated manner. In addition,

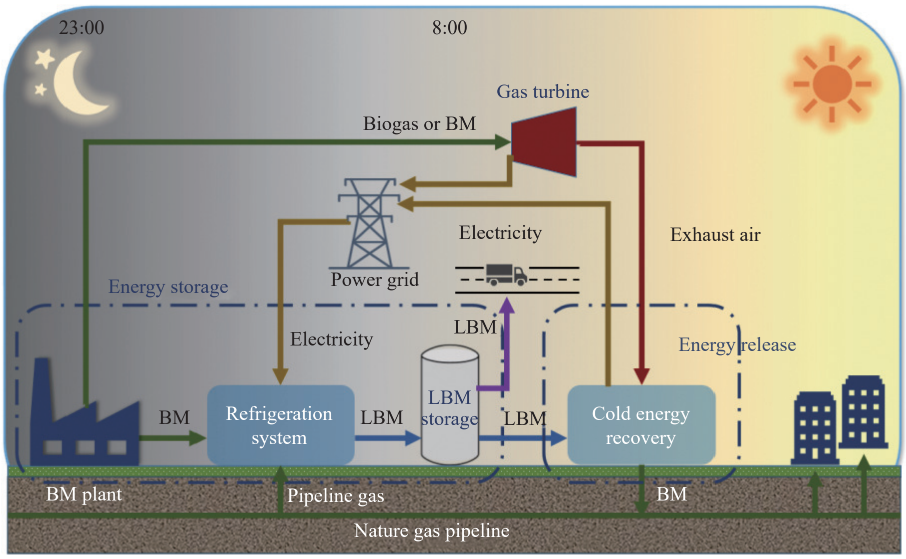

Figure 9 Gas electric dual peak shaving energy storage system based on regional bio natural gas system

using BNG as a low-temperature energy storage medium can have dual potential for both chemical and physical energy storage.

The schematic diagram of the plan is shown in Figure 9. Natural gas is converted into LNG using valley electricity, and LNG is gasified during peak electricity consumption to obtain natural gas. During this period, power cycle generation is used for peak shaving. At the same time, the cold energy of LNG gasification and the heat energy of internal combustion engine exhaust gas are used to co-produce electricity, realizing the effective recovery of cold energy. The power generation efficiency of this combined system can increase the independent generator system from 38% to 46%. Based on a daily production of 50 000 m^3 of biogas station, it can reduce approximately 5100 tons of carbon dioxide emissions per year, with significant carbon reduction effects.

7 Conclusions

Against the backdrop of global warming and greenhouse gas emissions reduction, the BNG industry is flourishing. BNG, as a clean energy source, is an important support for achieving the goal of keeping the 28th Conference of the Parties (COP28) away from fossil fuels. This study reviews the current development status and policy analysis of China and other regions of the world's BNG industry. The results show that BNG, as an emerging industry, has received attention from countries around the world, including China, and the level of industry development has been improved.

However, in recent years, as the BNG industry has become an independent industry, many issues that previously did not require attention as a subsidiary industry have become prominent, hindering the development of the industry. The main problems include low efficiency of mixed and collaborative fermentation of multiple materials, high overall energy consumption of the project, and difficulty in treating biogas slurry and tail water. Therefore, continuous technological innovation is necessary to promote sustainable and healthy development of the industry. This article takes the Anhui Funan Bio-natural Gas Project in China as a case for analysis, and elaborates in detail on the technological innovation and industrial achievements that the Funan Project has achieved. It mainly includes the development of new bio-electrochemical systems and low-temperature fermentation technologies to improve the efficiency of biogas production, efficient stirring technology for multi-material mixed collaborative fermentation, overall energy management strategies for engineering, and technologies for nutrient recovery and new material development in biogas slurry. On the basis of the above, suggestions are made on the development direction of the biogas industry, including the completeness of industrial technology, the objectivity of industrial regional development and the inevitability of the comprehensive benefits of the industrial chain.

Finally, based on the three major demands of new energy fuels, electricity, and energy storage, two novel energy systems based on BNG and coordinated development of multiple new energy sources are proposed: a new system for green electricity, green hydrogen production, transportation, storage, and supply based on regional BNG systems, and a regional energy storage system with dual peak shaving of gas and electricity.

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