atmosphere

MDPI

Article

Co-Production System Based on Lean Methane and Biogas for Power Generation in Coal Mines

Feifei Yin [1], Baisheng Nie [1,2,3,4,*], Yueying Wei [1] and Shuangshuang Lin [1]

[1] State Key Laboratory Coal Resources and Safe Mining, School of Emergency Management and Safety Engineering, China University of Mining & Technology (Beijing), Beijing 100083, China; harperyin@163.com (F.Y.); 18722071250@163.com (Y.W.); linss0917@163.com (S.L.)
[2] State Key Laboratory of Explosion Science and Technology, Beijing Institute of Technology, Beijing 100081, China
[3] State Key Laboratory of Coal Mine Disaster Dynamics and Control, School of Resources and Safety Engineering, Chongqing University, Chongqing 400044, China
[4] Xinjiang Institute of Engineering, College of Safety Science and Engineering, Urumqi 830023, China
* Correspondence: bshnie@cumtb.edu.cn; Tel./Fax: +86-10-82375620

Abstract: The problem of low efficiency of coal mine methane utilization is caused by the concentration of methane of less than 10%, or a concentration that varies dramatically directly emitted into the atmosphere. This work deals with the concept of a co-production system that blends lean methane and biogas to produce electric energy. It is recommended to add the biogas generated by straws around the mines in a controlled manner to the lean methane flow to obtain the desired gas concentration in order to generate electricity. Potential electricity generation and reduced greenhouse gas emissions were also evaluated. The result shows that the co-production system can significantly improve the utilization efficiency of lean methane in coal mines; the average use of pure methane in three coal mines is 0.18, 1.12, and 5.32 million m^3 every year, respectively, and the emission reduction effect of carbon dioxide (CO_2) equivalent is, respectively, 3081, 18,796, and 89,050 tons. The electricity generated and the economic environmental benefits of the co-production system are remarkable, and it has economic feasibility and broad perspectives for popularization. It not only has the advantage of improving the utilization rate of methane and biomass and providing power supply and heat source for mines, but also has practical significance in terms of saving energy, reducing environmental pollution, adjusting the energy structure, and achieving the target of carbon emission peak and carbon neutrality.

Keywords: lean methane; biogas; co-production system; power generation; energy conservation and emissions reduction

Citation: Yin, F.; Nie, B.; Wei, Y.; Lin, S. Co-Production System Based on Lean Methane and Biogas for Power Generation in Coal Mines. *Atmosphere* **2022**, *13*, 803. https://doi.org/10.3390/atmos13050803

Academic Editor: Dmitry Belikov

Received: 28 March 2022
Accepted: 12 May 2022
Published: 14 May 2022

1. Introduction

As a crucial foundation resource of China, coal has supplied the essential position of primary energy production and consumption in China for a long-time period, and has a substantial impact on economic and social development [1]. The energy production and consumption in China from 2010 to 2019 is illustrated in Figure 1 [2]. Although coal production and consumption in China have slowed in recent years, its dominant role in the country has not changed. Coal will remain the primary source of energy and the driver of national economic development [3,4]. Additionally, as the largest global coal producer and energy consumption, carbon dioxide emissions from fossil fuels are among the highest in the world. It is important to note that carbon emissions associated with coal is not limited to final combustion, and in the coal mining process, methane in a concentration less than 10% or that varies dramatically cannot be effectively utilized; thus, it is released wastefully into the atmosphere. It is worth emphasizing that methane is the second biggest anthropogenic greenhouse gas (GHG) after carbon dioxide (CO_2), with a global warming potential of 28–34 times greater than that of CO_2 over 100 years [5], which is a major contributor to exacerbating global climate change [6,7]; global warming has gradually become an environmental issue that requires immediate attention. In response to actively global climate change and sustainable development, China has announced to strengthen its Nationally Determined Contributions (NDCs) by reaching a carbon peak in 2030 and achieving carbon neutrality by 2060 [8]. Furthermore, with the rapid development of modern industry, energy demand grows at a rapid rate, resulting in a shortage of available fuel sources [9]. The evident conflict between environmental protection and the fast-growing economy poses a challenge to China's future development. Therefore, the low-carbon transformation of the energy system is a necessary way to achieve emission reduction targets [10].

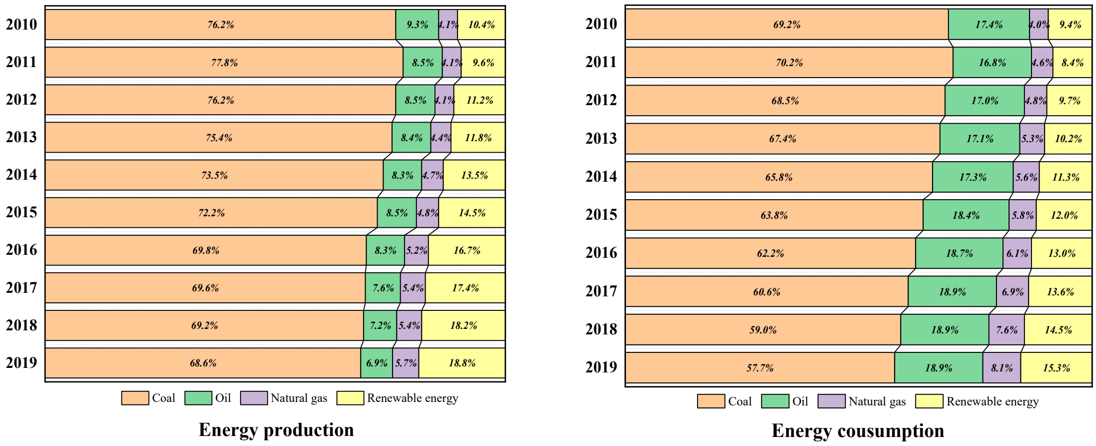

Figure 1. Energy production and consumption in China from 2010 to 2019.

As a byproduct of coal mining, coal mine methane is regarded as an ideal candidate for a low-carbon transition of energy system since its combustion and utilization produce carbon emissions that are much lower than fossil fuels [11]. It is supposed to serve as a substitute fuel to make up for the shortage and instability of renewable energy. Therefore, using coal mine methane sources directly benefits the environment by decreasing greenhouse gas emissions to the atmosphere, but also can create vastly economic profits. The underground coal mine methane extraction, utilization amount, and utilization ratio in China from 2008 to 2020 is shown in Figure 2. As can be seen, although the utilization amount has significantly increased, the utilization rate is still below 45% [12]. Most of the methane from underground coal mines belongs to low-concentration methane (CH_4 < 30 Vol%), which is very difficult to utilize due to the unstable gas source conditions and the limitation of traditional combustion techniques. It is worth mentioning that the multi-generation system has become a trend for sustainable development of energy and the environment. Related studies have shown that the realization of an energy system in coal mines with the methane power generation as the core can alleviate the energy demand of coal mines, achieve significant economic savings, and reduce greenhouse gas emissions [13–15].

Biogas production is one of the many methods for sustainable utilization of waste resources to produce fuels without increasing carbon dioxide in the environment [16], which can be used to alleviate global warming, energy security, and waste management [17]. By evaluating the methane production of digestive juice and solid separation of digestive juice, Sambusiti et al. [18] considered that recovering methane from biogas is feasible. It is worth noting that biomass produces biogas with a methane content of 50% to 70% [19]. Moreover, biomass has been a hot spot in power generation research due to its low sulfur and zero carbon dioxide emissions; its use for power generation can reduce dependency on fossil fuels, enhance energy utilization efficiency, and have positive feedback on alleviating the global greenhouse effect [20–22]. China has abundant biomass energy resources, and the total organic waste is about 460 million tons of standard coal equivalent per year [23].

However, the development utilization rate is less than 5%. Biomass power generation accounts for less than 1% of total power generation in China, and renewable energy generation accounts for only 3.5% [24]. For the moment, the development of biomass energy lacks a good model, and biogas plants may be difficult to sustain from a financial perspective [25]. However, using biogas to generate electricity can effectively eliminate agricultural and forest residues immediately, thereby reducing the carbon emissions resulting from the direct combustion of field residues, decreasing the risk of potential fires and pests to environmental damage [26–29].

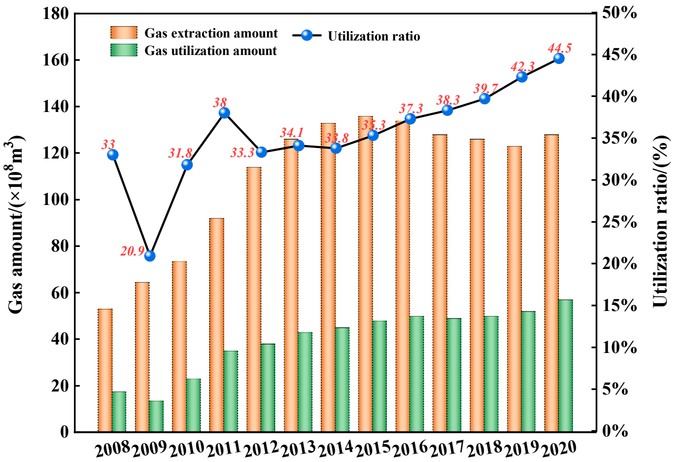

Figure 2. Underground coal mine methane extraction, utilization and utilization ratio in China.

Methane is considered as a potential energy source in the future and the key to the sustainable development of human society. Thus, reasonable recovery and utilization of coal mine methane have the dual significance of energy saving and environmental protection. In response to the challenge of clean, efficient, and sustainable development of coal mines, a co-production system based on lean methane and biogas to generate electricity in coal mines is proposed. Focusing on methane concentration that is extremely low and demonstrates dramatic volume changes, the biogas produced by biomass is introduced to the above methane flow in a controllable way, to attain a certain extent the mixed gas which meet the demand for power generation. Similarly, mixed gas is beneficial in resolving the challenges associated with unstable gas sources. The co-production system can comprehensively utilize the lean methane and adjacent biomass resources in coal mines. It is a beneficial way to achieve China's goals of carbon emission reduction and transition to clean energy. This study provides an opportunity to improve energy efficiency while also reducing greenhouse emissions. It will develop a novel model to address single energy development and utilization in mining areas, as well as provide a new way of thinking for optimizing energy distribution, which is conducive to the sustainable development of the economy and environment.

2. Materials and Methods

2.1. Materials

2.1.1. Coal Mine Methane

Coal mine methane (CMM) formed during the coalification process is retained within the coal seam and adjacent rock layers. The quantity of gas emitted from mining activities is determined by the coal rank and depth of burial in the coal seam. The reserves of coal mine methane resources buried at depths less than 2000 m reach approximately 3.681 $\times$ 10^{13} m^3 in China, closer to that of the continental natural gas resources and placing it third in the world. As clean energy with a high calorific value, it has attracted more and more attention [30,31], but it is also a major hazard in coal mine production. Gassy mines and outburst-prone mines account for more than 48% of the total coal mines in China. Therefore, CMM extraction is conducted following coal mine safety regulations to ensure the safety of coal miners. At present, there are two ways to exploit coal mine methane in China: ground drainage by surface drilling (CH_4% > 30%) and underground drainage through underground boreholes, roadways, and gas extraction pipes for draining the gas from the target coal seam (1% < CH_4% < 30%). However, the total extraction rate is less than 50%, and most of the methane is still removed from working mines via ventilation techniques into the atmosphere is known as Ventilation Air Methane (VAM, CH_4% < 0.75%). With the increase in methane extraction scale, annual production increases. Applicability of CMM utilization technologies is greatly dependent on the methane concentration. Generally speaking, it can be classified in the following ways: high concentration methane (CH_4 > 80%), medium concentration methane (CH_4 > 30%), low concentration methane (10% < CH_4 < 30%), lean concentration methane (1% < CH_4 < 10%), and ventilation air methane (CH_4 < 1%, VAM) [32]. In addition, the proportion of each category listed above accounts for 1%, 5%, 11%, 13%, and 70% of the total methane emissions from coal mines in China. It should be pointed out that the varying concentrations of coal mine methane correspond to different utilization technologies as clarified in Figure 3. Notably, coal mine methane concentration is less than 10%, accounting for 83% of the total coal mine methane resources, which are extremely difficult to utilize due to the risk of explosion and the limitations of traditional combustion techniques. Additionally, most unutilized methane is usually discharged directly into the atmosphere, which causes serious air pollution and a huge waste of clean energy [33,34]. Therefore, efforts should be made to improve the utilization efficiency of lean methane (CH_4 < 10%), so as to alleviate the energy crisis, effectively utilize waste, and minimize air pollution.

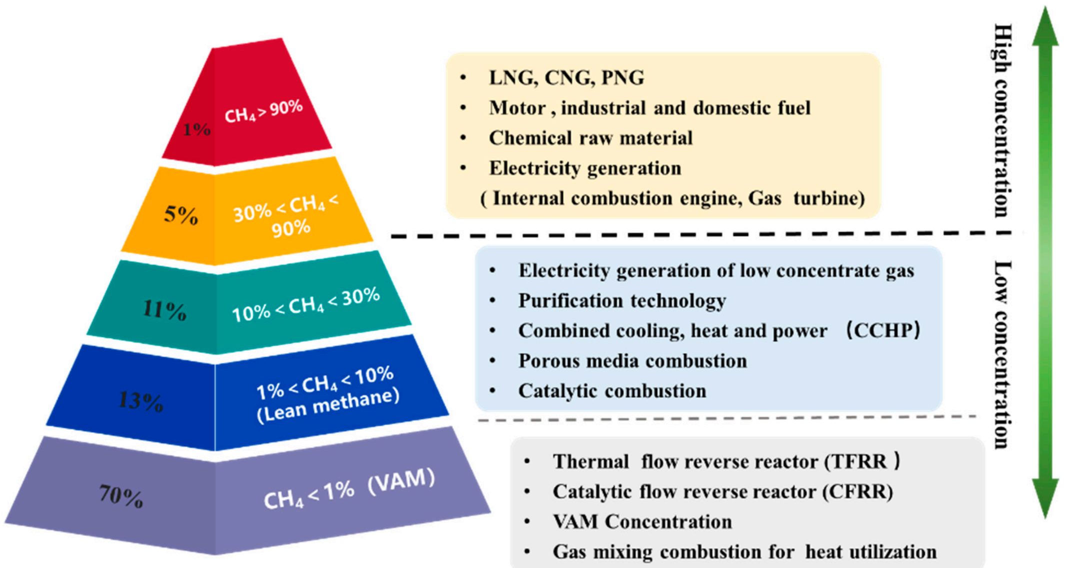

Figure 3. Utilization technologies of coal mine methane with different concentrations.

2.1.2. Biogas from Biomass

As a primary agricultural production country, China has abundant biomass resources, which are mainly consisted of crops, forestry crops, and their waste byproducts, animal residues, and organic fractions of municipal solid wastes (MSW); the proportions are 36.18%, 16.33%, 37.72%, and 9.77%, respectively [35,36]. Biogas derived from biomass is a potential renewable source of methane energy, and various concentrations have formed in the fermentation process. In general, the CH_4 content in biogas is 50–70%. Furthermore, the chemical composition of biogas is mostly determined by the kind of decomposed raw materials, which might lead to slight differences in composition. When biogas is used to produce heat or electricity energy, it can contribute to reducing greenhouse gas emissions, diversifying the energy supply, and decreasing dependence on fossil fuel markets [37]. Its digestion residues can be used as fertilizer, which will have a positive effect on crop production, leading to an increase in crop yield. In terms of green development, biogas production and its subsequent use in energy production have obtained considerable attention. Research and feasibility analysis of the existing biogas plants has found that crops such as straw are dominant. Straw as a raw material for biogas production, which can relieve serious pollution of the environment by burning in fields after harvest and possibly eliminate potential disasters such as fires. Consequently, the biomass raw materials in this paper are mainly agricultural straws collected around the mining area. It will be more economical due to the transport distances are relatively short.

2.2. Co-Production System Description

A power generation system requires a methane content of up to 7% in the mixed gas [38]. From a practical point of view, most of the lean methane concentration is lower than 5%, and a part of the methane concentration has changed drastically, which results in a large amount of methane cannot being effectively utilized and directly emptied. To improve energy efficiency, a co-production system based on lean methane and biogas for power generation in coal mines is put forward, the general schematic is shown in Figure 4. A quite high value of methane in the feed stream above 7% was attained by blending lean methane (CH_4 < 5%) with biogas, which will enable its use in the already existing devices that require higher contents of the combustible component for power generation. When the methane is sufficiently high, a surplus of thermal energy is produced, which can be transformed into electricity and other uses. The implementation and application of this system not only help to realize the full utilization of waste energy, improve the utilization rate of low concentration methane, and alleviate the shortage of existing energy supply, but also helps to form a sustainable energy supply.

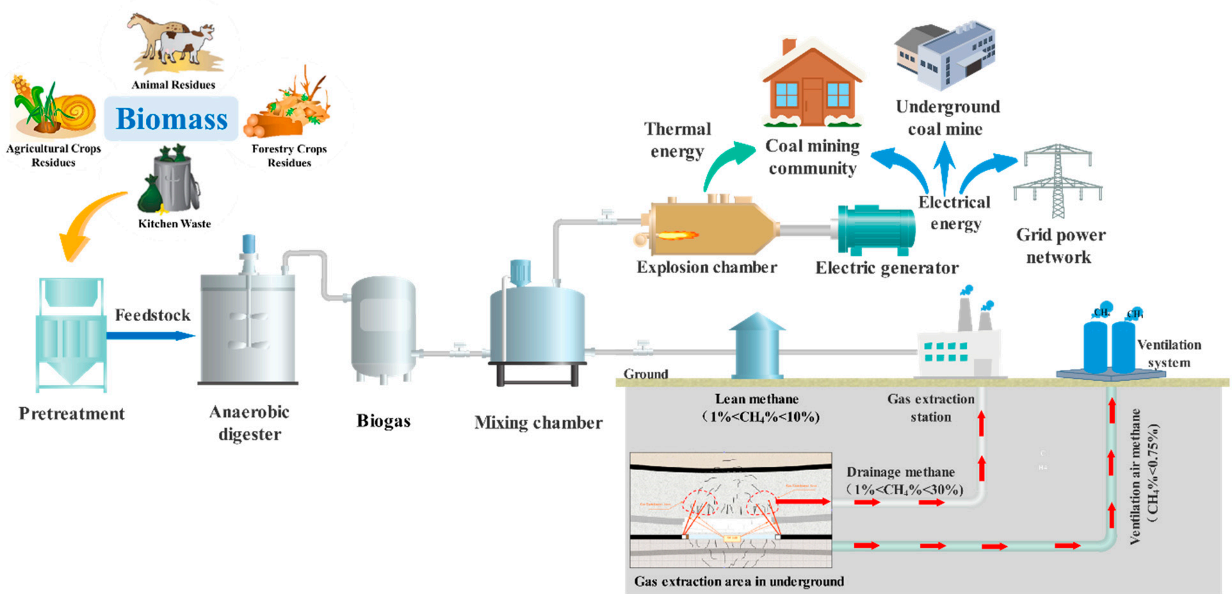

Figure 4. Co-production system with lean methane and biogas for power generation.

The control principle of the co-production system is illustrated in Figure 5. Methane fluctuation was monitored in real-time by flow and concentration sensors. At the same time, biomass is controllably injected into the anaerobic digester and adjusts the biogas output regularly. The biogas storage tank is set up in the process to buffer the biogas volume mixed into the lean methane pipeline. Through the controller, the valve opened and closed gradually. The system can regulate the mixed gas to more than 7% enough to be utilized to generate power by conventional methane-fueled engines. When biogas and lean concentration methane concentrations change, the monitoring system of the gas regulator will adjust the intake flow rate in real-time to achieve the desired methane concentrations. Thus, the methane concentration outlet of the mixing device will remain unchanged, providing a reliable and stable gas source for the normal operation of the power generation system.

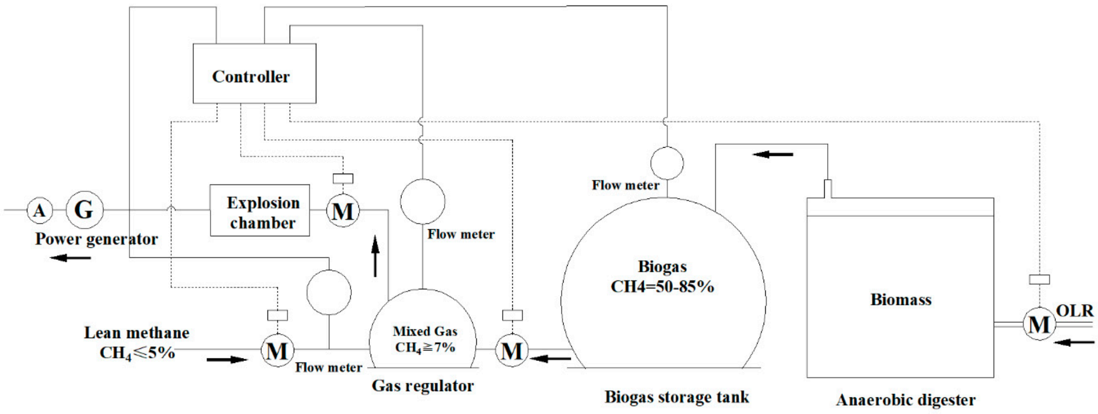

Figure 5. Control system of the lean methane and biogas co-production in coal mines.

2.3. Models Calculation

2.3.1. Biogas Energy

The produced biogas originates from different feedstocks, such as crops, forestry crops, animal residues, and organic fractions of municipal solid waste. Energy generated from these sources via anaerobic digestion reduces methane emissions to the atmosphere. Of course, the potential efficiency of gas production varies depending on the different raw materials. For animal manure, the biogas production potential for cows, pigs, and poultry is 0.25 m^3/kg, 0.38 m^3/kg, and 0.48 m^3/kg, respectively [39]. One of the strategies to reduce GHG emissions, as well as the generation of renewable energy, consists of producing biogas from MSW. The share of MSW organic fraction and volatile solids is approximately 80.2% and 76.2%, respectively, and the potential yield for biogas generation was considered 222 m^3/t [40]. However, the ideal feedstock for biofuel generation should be low cost and emissions and high efficiency. China is the main producer of grain, and most coal mines are located in rural and mountainous areas, where crops are plentiful [41]. Traditionally, crops straw had been utilized through direct combustion. Burning straw produces pollutants including dust and acid rain gases such as Sulphur dioxide and nitrogen oxides. However, the straw captured by the farmland around the mining area as a raw material to maintain the supply of biogas fuel [42], which can effectively enhance the utilization efficiency of biomass resources, and the pollution caused by open-field burning of straw can be reduced, in line with the strategic needs of sustainable development. Further, renewable energy from straw is available as a domestic resource in the rural areas, which is not subject to world price fluctuations or the supply uncertainties as of imported and conventional fuels. Overall, for every ton of grain produced, 1.5 tons of straw are available. Acting in accordance with research from Braun and Welinger [43], the amount of methane produced per kilogram of dry straw is 200–300 L. Generally, the calorific value of biogas depends on the methane content of the biogas, and the caloric value of pure CH_4 is 35.88 MJ/Nm^3 [44]. If the biogas consists of methane are 60%, having a caloric value of 21–25 MJ/Nm^3. However, the assessment of straw recovery and utilization rate relies on the yield of straw resources. The quantity of straw resources that can be collected and utilized refers to the maximum amounts of straw resources that could be gathered from the field and utilized by people under actual cultivation management. According to the total straw yield and utilization coefficient, the amount of collectible straw can be calculated [45]. Therefore, the total amount of straws to match the co-generation system in coal mines can be calculated by

$$W_{GS} = W_S/GI \tag{1}$$

Note: W_{GS} is the yield of straw, t; W_S is the required volume of straw resources to produce biogas, t; and GI is the collectible coefficient of straw resources, generally being 0.85.

The single production of farmland straw refers to the total straw yield per unit area of farmland in a certain area, and its value can reflect the comprehensive production capacity of farmland straw in a region. Therefore, the total area of farmland required for the co-generation system of energy in coal mines is

$$A_{CL} = W_{GS}/y_{SL} \tag{2}$$

Note: A_{CL} is the total area of farmland, hm^2; W_{GS} is the total straw yield, t; and y_{SL} is the single yield of farmland straw, kg/hm^2.

2.3.2. Estimation of GHG Reduce Emissions

The greenhouse gas emissions generated by coal mines are principally composed of CH_4, CO_2, and N_2O, and CH_4 constitutes about 30–90% from coal-mining activities and with a global warming potential of 25 times over a 100-year time horizon, where the reference is used for carbon dioxide. Therefore, its mitigation through the use of relevant technologies is of paramount importance. The assessments of GHG reduction emissions were based on the recommended methods by the Intergovernmental Panel on Climate Change (IPCC) Guidelines for National Greenhouse Gas Inventories [46]. The total equivalent of CO_2 emissions (kg) can therefore be expressed as

$$E_{CO_2} = E_{CH_4} \times GWP_{CH_4} \tag{3}$$

For this calculation, E_{CO_2} is the CO_2 equivalent of CH_4; the GWP is the global warming equivalent factor of CO_2 for methane and the value is 25.

2.3.3. Determination of Electricity Generation Potential

Coal mining is considered an energy-intensive process, which requires significant electricity loads to run pieces of equipment, mainly including mining machines, conveyor belts, desalination plants, coal preparation plants, and ventilation fans. In general, a large amount of electricity is required because the types of equipment operate around 24 h a day [47]. What is noteworthy is that methane power stations can be established in coal mines, which can not only facilitate the utilization of emission CH4 but also reduce energy consumption in the production process. The electrical energy (KWH) that could be obtained by the co-production system is estimated as

$$P = \frac{Q_{CH_4} \times C_{CH_4} \times \rho \times L \times \lambda \times \eta}{3.6} \tag{4}$$

Note: P is the amount of power generation potential in the co-production system. L is a fuel calorific value 55.9 MJ/kg for methane [48]; Q_{CH_4} is the amount of methane utilization in the co-production system, m^3; C_{CH_4} is the content of methane, vol%; ρ is the methane density, as 0.67 kg/m^3; λ is the methane concentration, 95%; and 3.6 is the conversion factor from MJ to kWh, where η is given 35% as the generator efficiency [49].

2.4. Case Studies

Methane is associated with the coalification process and is released into the working face during the underground operation, posing a safety hazard for miners and machinery deployed in the mine. With the improvement in mechanization degree, the amount of coal mine methane extracted has progressively increased. The location of the three coal mines selected in this study is shown in Figure 6. According to coal production and IPCC emission factors [50], estimates of methane emissions have been presented in Table 1. Methane gas emissions to the atmosphere in the DSC coal mine are observed 0.011 Tg in the lower case and 0.029 Tg in the upper case. And methane emissions from the CC coal mine and the

JC mine are 0.059~0.155 Tg and 0.065~0.175 Tg, respectively. However, the utilization rate of methane from coal mines is still lower. The key to this phenomenon is that most lean methane is difficult to use by conventional combustion technology since the gas volume is large and its concentration variable. Methane is transformed into CO_2 and water through oxidation or combustion, and the GHG effect can be significantly reduced. Therefore, there is an urgent need to upgrade the utilization rate and reduce the methane content in the atmosphere.

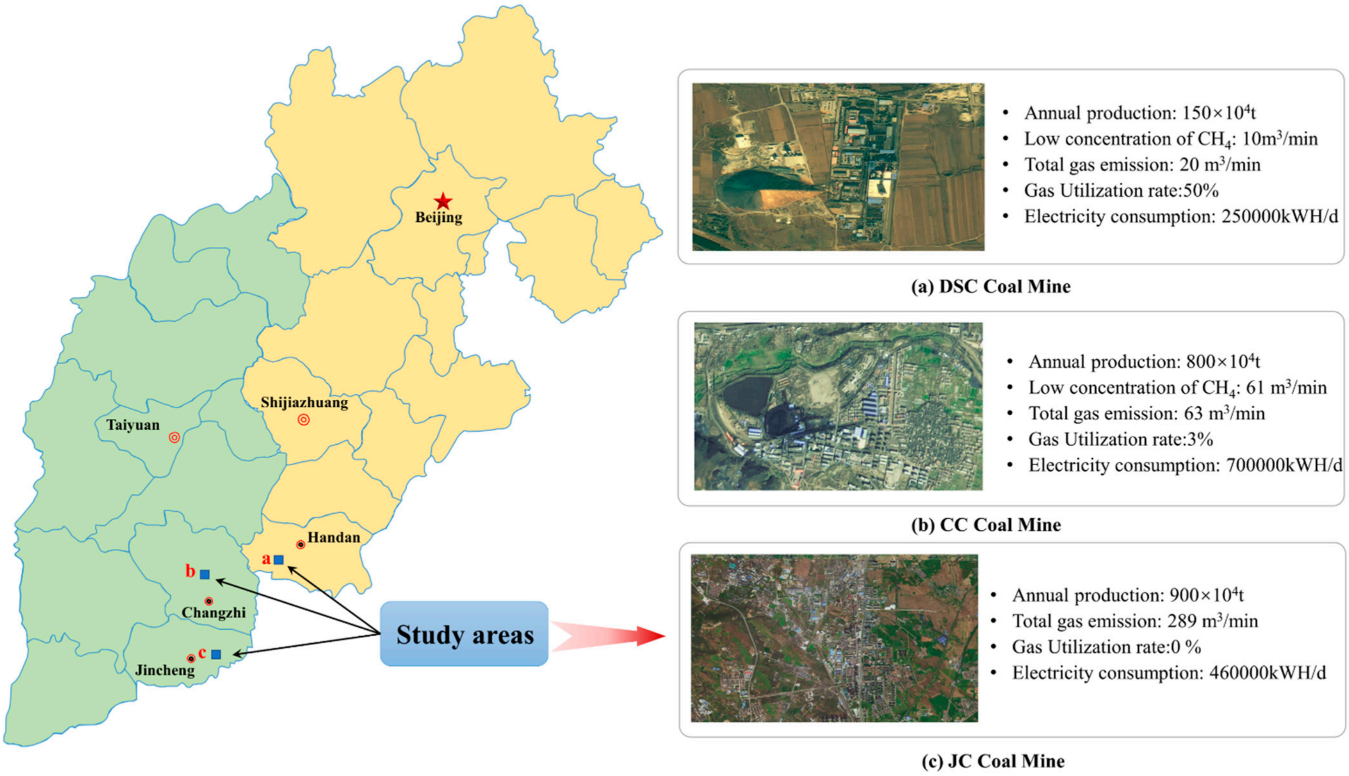

Figure 6. Location of the study coal mine area in China.

Table 1. Methane emission from coal mining and post-mining for the coal mines.

Coal Mines	Coal Production /×10^4 t	IPCC Emission Factors /(m^3/t)		Methane Emission /Tg
DSC	150	Mining	10~25	0.010~0.025
		Post-mining	0.9~4.0	0.001~0.004
		Total		0.011~0.029
CC	800	Mining	10~25	0.054~0.134
		Post-mining	0.9~4.0	0.005~0.021
		Total		0.059~0.155
JC	900	Mining	10~25	0.060~0.151
		Post-mining	0.9~4.0	0.005~0.024
		Total		0.065~0.175

Particular attention should be paid to the fact that the vast majority of coal mines are located in rural or mountainous areas, which have abundant biomass resources, such as straw, livestock manure, and so on. In addition, the available open space is relatively wide, which is very suitable for implementing an energy co-production system for power generation around the coal mines. In a high-emitting methane mine, there is more potential for an energy co-production system in coal mines. In this paper, the co-production system based on lean methane and biogas in coal mines was implemented, to evaluate the development potential for power generation, energy efficiency, and greenhouse reduction effect in these areas.

3. Results and Discussion

3.1. Case Analysis

Capturing and utilizing lean methane is a proven challenge, but new technologies that oxidize methane to CO_2 can bring enormous economic and environmental benefits. Different coal mines with a gas extraction utilization efficiency of 50%, 3%, and 0% are selected to implement the energy co-production system; estimates of lean methane emissions in coal mines are shown in Table 2. This study focused on gas concentrations below 5%, assuming that the concentration of lean methane is 4% and 3%, respectively. Subsequently, the mixed gas concentration available for power generation is obtained by mixing lean methane with biogas. It should be pointed out that 7% is the lowest CH_4 concentration that can be used for power generation in practical technical applications at present. As shown in Figure 7, the lean methane with a concentration of 4% and 3%, to reach the target gas concentration (7%), the amount of biogas required in the three coal mines is 13 m^3/min and 23 m^3/min, 78 m^3/min and 140 m^3/min, and 360 m^3/min and 640 m^3/min, respectively. Biogas production mainly relies on biomass raw materials around the mine, and that is worth noting that most coal mines in China are in rural areas, which are abundant in straw and other raw materials. According to the relevant calculation in Section 2.3.1, the requirements of straw quantity and farmland area of the three coal mines matching the energy co-production system for power generation are obtained. The results are presented in Table 3, and it is apparent that the demand for farmland and straw is linearly associated with lean methane emissions. Among them, the demand for DSC coal mine is the smallest, CC is six times more than DSC, and the JC is the largest demand, which is five times that of CC. It is anticipated that the co-production system can use surrounding biomass energy efficiently and logically.

Table 2. Lean methane emissions estimation for coal mines in three regions.

Parameters	Rate/Production		
Coal Mine	**DSC**	**CC**	**JC**
Gas utilization efficiency (%)	50	3	0
Lean methane (m^3/min)	10	61	289
Lean methane discharge in one day (m^3)	14,400	87,840	416,160
Lean methane discharge in one year (Mm^3)	5.26	32.06	151.90
Lean methane emitted @ 4% CH_4 (*v/v*) (Mm^3)	0.21	1.28	6.08
Lean methane emitted @ 3% CH_4 (*v/v*) (Mm^3)	0.16	0.96	4.56
Average Lean methane estimate per year (Mm^3)	0.18	1.12	5.32
Quantity of lean methane emission per year (t)	123	752	3562
Global Warming Potential equivalent CO_2 (t)	3081	18,796	89,050

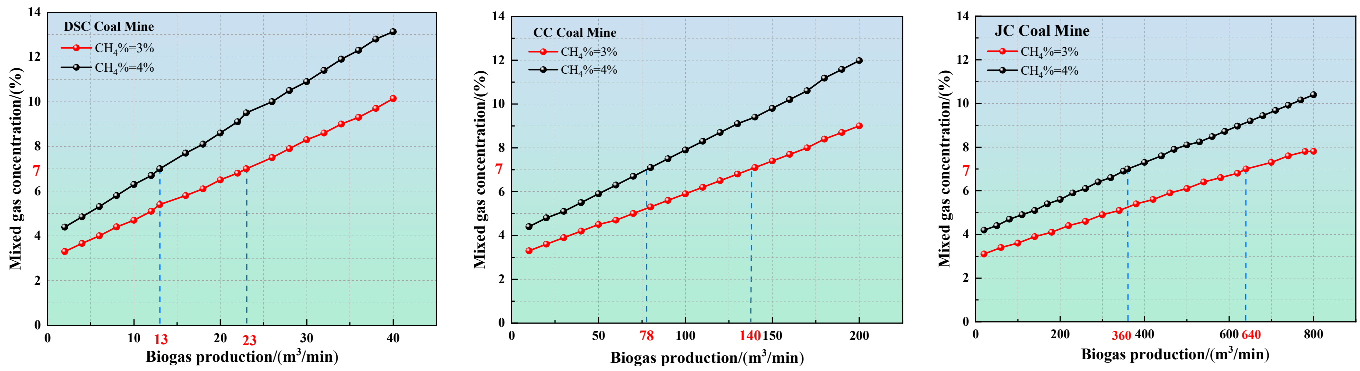

Figure 7. The amount of biogas production to meet required by the co-production system.

Table 3. Parameters of the co-production system for power generation in coal mines.

Coal Mine	CH_4 Concentration	Biogas Demand (m^3/min)	Straw Demand (Ton/d)	Farmland Area (acre)
DSC	3%	23	129.9	47,402
	4%	13	73.4	26,793
CC	3%	140	790.6	288,536
	4%	78	440.5	160,756
JC	3%	640	3614.1	1,319,021
	4%	360	2032.9	741,949

3.2. Comprehensive Analysis of Co-Production System

3.2.1. Energy Savings

The coal mining area needs to consume a lot of energy during routine production, and at the same time, it will emit a lot of lean methane that can be used to generate electricity through the energy co-production system. The consumption of electricity (MWH/d) in coal mining areas and products obtained from the co-production system in coal mines is illustrated in Figure 8. In the DSC coal mine, 40.85 MWH and 70.24 MWH of electrical would be generated per day at the lean methane concentrations are 4% and 3%, and it accounts for 16.34% and 28.09% of the daily power consumption. Clearly, electricity production through the energy co-production system is quite different in the three mining areas. Similar to the DSC Coal Mine, the production of electricity in the CC coal mine also can meet part of the electricity demand due to its electricity generation rate reaching 35.04% and 61.08%, respectively. In addition, the electricity generation rate of the JC coal mine is as high as 246.42% and 425.21%, which can not only meet the demand of the coal mine itself, the excess electricity can be connected to the power grid for the surrounding residents and other users. According to CNY/¥0.64/KWH, the economic advantages of power generation are lucrative. Therefore, it is a greater development potential to implement coal mine energy co-production systems in these areas, which will be beneficial to improve the utilization efficiency of lean methane and biomass resource but also can reduce the consumption of other fuels in order to satisfy the huge power load in the mining area.

More than 48% of the major state-owned key coal mines are high-gas or outburst mines in China, and they are relatively rich in coalbed methane. According to the current utilization technology, methane with a concentration of higher than 30% can be used effectively. However, the use of lean methane is difficult because the content of CH_4 is low and varied, which is generally emitted directly into the atmosphere. Not only does it cause waste of clean energy, but also has a serious impact on climate change. On the other hand, there is abundant straw and other raw materials around coal mines, but the development capacity of the biogas system in China is less than 5%, and the utilization rate of biogas energy needs to be improved urgently. As is well known, the coal mining process demands significant power consumption, the co-production based on lean methane and biogas can provide an effective power supplement for mine production and the heat generated by the waste heat of the power plant and biogas system can provide heating for the coal mine wellhead, partially replacing the existing boilers in the coal mine. Meanwhile, biogas not only provides the heat source for the daily life of mine residents, but is used as fertilizer for the farmland around the coal mine. In conclusion, the execution of the co-production system can accomplish the comprehensive and rational utilization of resources, save fossil fuel consumption to a certain extent, and slow down the carbon dioxide emission caused by the combustion of fossil energy. At the same time, the utilization of gas is also conducive to reducing the harm of mine gas explosions and ensures the safety of coal mine production. Moreover, a mass of straw demand can make the surrounding organic waste into valuables, maximize the utilization value of waste energy, and the space occupied by organic material stacking and the potential fire risk can be reduced.

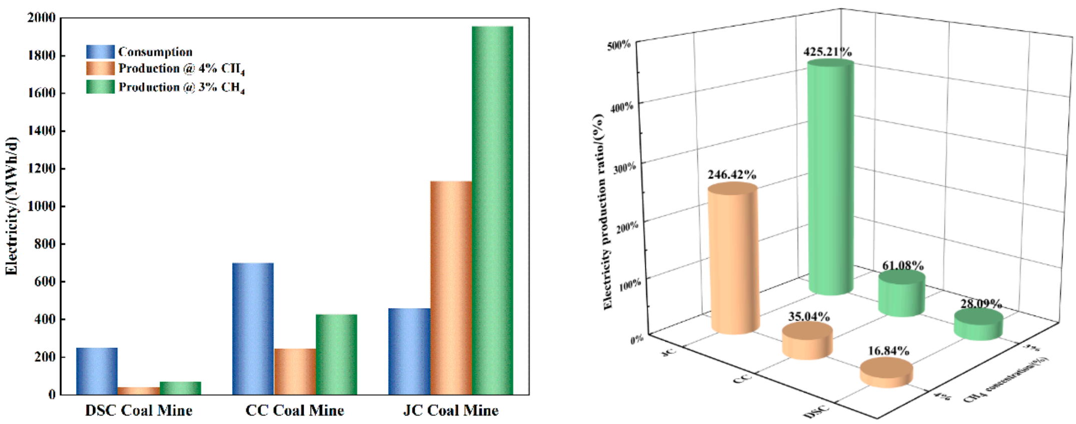

Figure 8. The quantity of electricity energy production from the co-production system in coal mines.

3.2.2. Economic and Environmental Benefits

From the perspective of globalization, the issue of energy consumption has become a key problem in economic and environmental protection fields [51]. The development and utilization of energy cause a deficit in the ecological environment, which is a common problem facing all countries in the world. Much use of fossil energy causes great environmental pollution, especially great greenhouse gas emissions like CO_2. Therefore, low-carbon development has become a strategic choice for countries around the world to ensure sustainable economic and social development. The key to a low-carbon strategy is to reduce carbon dioxide emissions through relevant measures and promote the efficient use of the energy industry and green and sustainable development.

The co-production system is based on lean methane and biogas to produce electricity, which takes into account economic and environmental benefits. It can significantly improve the utilization efficiency of lean methane and biomass energy and help reduce the content of methane in the atmosphere. In addition, it would provide an opportunity to earn carbon credit by selling a Certified Emission Reduction (CER) through a Clean Development Mechanism (CDM) project. Whether the co–production system can be received and applied in the industry in the future mostly depends on whether the system can bring economic benefits. Consequently, an economic evaluation is necessary to be done. In this study, a preliminary economic analysis was performed to determine the applicability of co-production that lean methane mixture biogas for coal mines. With the technical basis, every co-production system has its specific cost elements. Thus, the economic analysis of this study is covering a co-production system handling lean methane with concentration is 0.4% and 0.3% were assessed. The cost of the co-production system is complex due to it consisting of a lean methane collection and delivery system, biogas pro-proceeding and production system, mixture system, and power generation system. To gain a rough idea of the typical costs of a simple, based on the integrity of the system, several parameters taken into account were equipment cost, operating and maintenance (O&M) cost, availability of the facility, and methane concentration and flow rate. Considering the daily maintenance of the system, the availability of the facilities to be constructed was assumed to be 85% for more reliable results [13]. However, the parameters of methane concentration, flow rate, and conversion efficiency have remained constant for all conditions. The total cost for a co-production system, including all essential installations, but not including land, is between 10,000 and 13,000 CNY KWH capacity. Operation and maintenance cost is taken as 5% of capital and the lifespan of this system is assumed to 20 years. Furthermore, the revenue components include a carbon credit and the profits from generated electricity. Table 4 summarizes the parameters used in the economic analysis of the co-production system in three coal mines. It can be seen that the emission reduction effect of different coal mines varies greatly. Such a significant effect of greenhouse gas emission reduction is a result of a combination of various factors in the system. In the DSC coal mine, the co-production system may combust and convert 2454.50 t or 4220.54 t methane to carbon dioxide per year, generating revenue of 8.27 or 14.22 million RMB by selling CERs. For the CC coal mines, with a methane utilization ratio of 3%, when the concentration of lean methane is 4% and 3%, the CO_2 emission reduction is 1013.30 Kt and 1766.29 Kt, respectively, and the emission reduction benefits may also reach 50~87 million RMB. Furthermore, the CO_2 emission reduction and revenue are approximately five times higher than that of the CC coal mine, because the methane emission in the JJ coal mine is very large and almost not used. In addition, the revenue from the electricity generated by the co-production system in coal mines is considerable. Through income and expenditure analysis, it was estimated that the capital cost of a co-production system would be recovered after two years of operation. Therefore, the co-production system based on lean methane and biogas operating in the coal mine is economically viable, energy-efficient, and environmentally beneficial, which is contributing to the realization of green, high efficiency, and sustainable development.

Table 4. Economic and environmental analysis by using lean methane and biogas in the co-production system.

Parameters	**Rate/Production**					
Coal Mines	**DSC**		**CC**		**JC**	
Lean methane emission (m^3/min)	10		61		289	
Lean methane concentration (%)	3%	4%	3%	4%	3%	4%
Biogas Demand (m^3/min)	23	13	140	78	640	360
Methane flow (m^3/min)	14	8	86	49	393	228
Methane conversion (%)	95	95	95	95	95	95
Facilities availability (%)	85	85	85	85	85	85
Use of methane (t/yr)	4220.54	2454.50	25,691.43	14,738.97	117,537.60	68,115.35
Use of methane eq. CO_2	11,606.49	6749.87	70,651.42	40,532.17	323,228.39	187,317.22
CO_2 reduction (Kt)	290.16	168.75	1766.29	1013.30	8080.71	4682.93
Revenue ((Million CNY¥/yr)	54.06	31.44	329.10	188.80	1505.61	872.53
From electricity	39.85	23.17	242.55	139.15	1109.66	643.07
From carbon credit	14.22	8.27	86.55	49.65	395.95	229.46
Total cost (Million CNY¥)	87.79	51.06	534.43	306.60	2444.98	1416.92
Installed cost (CNY¥/KWH)	10,000	10,000	10,000	10,000	10,000	10,000
O&M cost (CNY¥/KWH)	500	500	500	500	500	500

Note: the rate of certified emission reduction (CER) is $7.00.

3.3. Prospects and Challenges

In recent years, China has adhered to the concept of green development, vigorously developed clean energy, optimized the industrial structure, and gradually formed a low-carbon strategy centered on energy conservation, carbon reduction, and energy transformation. It has become a vital strategic research direction in the field of energy. At present, vigorously promoting the construction of ecological civilization the cogeneration system will help to reduce carbon dioxide emissions and the destruction of the environment caused by the development of coal resources. Moreover, it can effectively alleviate the current energy shortage crisis in China. The utilization of lean methane is the best method to reduce the methane load in the atmosphere, but it is a challenging task from a technical and economic point of view. Major challenges are low and variable methane concentration, changing the location of working faces, impact on mining operations, and large and costly air handling systems. Other challenges can be government policies, technological issues, and finances. For example, the terrain in China is complex, and most coal mines are located in mountainous areas. The establishment of gas power stations and thermostatically controlled biogas digesters will require significant human and financial resources. The operational cost of the co-production system is relatively high, which requires the support of the government in finance and policy. Some policies lack a healthy development environment in the process of implementation, and it is difficult for local governments to implement them accurately, which brings some challenges to the implementation of the project. However, these challenges can also be perceived as the ones versus reality. It is important to understand both, so that the right programmers can be designed to overcome these issues.

The co-production system in coal mines using lean methane combined with biogas can replace the original boiler equipment, which emits more pollution into the environment, saves operation costs, outputs heat energy for economic benefits, maximizes transformation and utilization of the available resources in the mining area, and reduces the dependence on fossil fuels. It is of great significance to improve the efficiency of energy use, promote the large-scale development of renewable energy, and realize the sustainable development of a low-carbon economy. The generated electricity can supply the daily electricity demand of the mining area itself and surrounding villages while partially connected to the grid creating economic benefits. It will not only save fossil fuels but also make full use of abandoned resources, realize the complementation and substitution of energy, and improve the comprehensive utilization of methane. On the other hand, the effective utilization of straw and other organic biomass reduces the pollution caused by carbon emissions and incineration, which are conducive to energy conservation and environmental protection. Furthermore, it can obtain the national financial subsidies for gas utilization; emissions reduction credits may help stimulate project development, particularly in cases where methane recovery would not otherwise be profitable or where destruction is the only project option. For large industrial and mining enterprises with sufficient gas sources or biomass energy, it is possible to introduce a co-production system of multi-energy, which can save energy and reduce greenhouse gas emissions and has a broad application prospect.

4. Conclusions

Methane is the second most important greenhouse gas after carbon dioxide, and its greenhouse effect is 25 times that of carbon dioxide. Coal mine methane is one of the principal sources of industrial gas emissions. Thus, coal mining must become more environmentally friendly to mitigate methane emissions. Reasonable recovery and utilization of coal mine lean methane have the dual significance of energy saving and environmental protection, and the co-production system based on lean methane and biogas for power generation in coal mines was put forward in response to clean, efficient, and sustainable requirements.

In order to comprehensively evaluate the economic and environmental benefits of the co-production system, three coal mines with respective methane utilization rates of 50%, 3%, and 0% were chosen. It should be noted that the average use of pure methane in the three mining areas can reach 0.18, 1.12, and 5.32 million m^3 every year, respectively, by the co-production system. The amount of biogas required for the system operation and the matching farmland area and straw quantity were discussed, which proves that the feasibility of implementing the co-production system in the mining area was certain. Moreover, potential electricity generation and greenhouse reduction were also evaluated. The results show that the electricity production rates of the three coal mines at the lean methane concentration of 4% are 16.34%, 35.04%, and 246.42%, respectively. And the emission reduction of CO_2 can reach 168.78 Kt, 1013.30 Kt, and 4682.93 Kt, respectively. While the concentration of lean methane is 3%, the electricity production rates are 28.09%, 61.08%, and 425.21% and the emission reduction of CO_2 is 290.16 Kt, 1766.29 Kt, and 8080.71 Kt, respectively. It's a good illustration that this system can effectively integrate the regional resources, convert waste into wealth, and realize energy saving, emission reduction, and sustainable clean energy in coal mines. A preliminary economic analysis was performed, which proved that the co-production system would be recovered investment costs after two years of operation. Hence, the co-production system is technically and economically feasible and has a certain value of popularization.

The co-production system is used to generate power and heat energy, which can replace some coal-fired boilers for power supply and heating for coal mining areas. It provides an opportunity to raise the energy utilization efficiency of isolated resources in the mining area and the waste energy and renewable energy at a low utilization rate and has good energy-saving and environmental protection benefits. At the same time, it can also bring economic benefits to coal mining enterprises. In addition, it will contribute to mitigating methane emission into atmospherics and achieve the goal of carbon emission peak and carbon neutrality, which are in line with the relevant policies of air pollution prevention and CMM utilization in China.

Author Contributions: Conceptualization: B.N.; methodology: F.Y. and B.N.; formal analysis and investigation: F.Y., Y.W. and S.L.; writing—original draft preparation: F.Y., Y.W. and S.L.; writing review and editing: F.Y. and B.N.; funding acquisition: B.N. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the National Natural Science Foundation of China [51974322]; the opening project of State Key Laboratory of Explosion Science and Technology (Beijing Institute of Technology) [KFJJ21-05M]; International Clean Energy Talent Program [201902720011]; the Fundamental Research Funds for the Central Universities [2009KZ03].

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Shen, L.; Gao, T.M.; Cheng, X. China's coal policy since 1979: A brief overview. *Energy Policy* **2012**, *40*, 274–281.
2. *China Statistical Year Book. National Bureau of Statistics of China*; China Statistics Press: Beijing, China, 2020. Available online: http://www.stats.gov.cn/tjsj/ndsj/2020/indexch.htm (accessed on 18 September 2020).
3. Li, Y.; Yang, X.D.; Ran, Q.Y.; Wu, H.T.; Irfan, M.; Ahmad, M. Energy structure, digital economy, and carbon emissions: Evidence from China. *Environ. Sci. Pollute. Res.* **2021**, *28*, 64606–64629. [CrossRef]
4. Wang, J.L.; Feng, L.Y.; Davidsson, S.; Höök, M. Chinese coal supply and future production outlooks. *Energy* **2013**, *60*, 204–214. [CrossRef]
5. *IPCC Climate Change 2014. Synthesis Report. Contribution of Working Groups I, II and III, Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; IPCC: Geneva, Switzerland, 2014; p. 151.
6. International Energy Agency (IEA). CO_2 Emissions from Fuel Combustion 2019-Highlights. 2019. Available online: https://webstore.iea.org/co2-emissions-from-fuel-combustion-2019 (accessed on 19 May 2019).
7. Jiang, X.; Mira, D.; Cluff, D.L. The combustion mitigation of methane as a non-CO_2 greenhouse gas. *Prog. Energy Combust. Sci.* **2018**, *66*, 176–199. [CrossRef]
8. Zhang, Y.F.; Shi, X.P.; Qian, X.Y.; Chen, S.; Nie, R. Macroeconomic effect of energy transition to carbon neutrality: Evidence from China's coal capacity cut policy. *Energy Policy* **2021**, *155*, 112374. [CrossRef]
9. Zhao, P.T.; Shen, Y.F.; Ge, S.F.; Chen, Z.Q.; Yoshikawa, K. Clean solid biofuel production from high moisture content waste biomass employing hydrothermal treatment. *Appl. Energy* **2014**, *131*, 345–367. [CrossRef]
10. Song, S.M.; Li, T.X.; Liu, P.; Li, Z. The transition pathway of energy supply systems towards carbon neutrality based on a multi-regional energy infrastructure planning approach: A case study of China. *Energy* **2022**, *238*, 122037. [CrossRef]
11. Kerr, R.A. Natural gas from shale bursts onto the scene. *Science* **2010**, *328*, 1624–1626. [CrossRef]
12. Wang, X.X.; Zhou, F.B.; Ling, Y.H.; Xiao, Y.N.; Ma, B.; Ma, X.Z.; Yu, S.B.; Liu, H.; Wei, K.W.; Kang, J.H. Overview and Outlook on Utilization Technologies of Low-Concentration Coal Mine Methane. *Energy Fuels* **2021**, *35*, 15398–15423. [CrossRef]

13. Baris, K. Assessing ventilation air methane (VAM) mitigation and utilization opportunities: A case study at Kozlu Mine, Turkey. *Energy Sustain. Dev.* **2013**, *17*, 13–23. [CrossRef]
14. Chen, H.L.; Wu, Y.F.; Yang, G.M.; Shi, J.; Zhou, W.; Bai, J.P.; Li, S.D.; Shao, Z.P. Direct Power Generation from Low Concentration Coal-Bed Gas by a Catalyst-Modified Solid Oxide Fuel Cell. *ChemElectroChem* **2018**, *5*, 1459–1466. [CrossRef]
15. Farzaneh, H.; Fahimi, M.; Saboohi, Y. Optimal power generation from low concentration coal bed methane in Iran. *Energy Sources Part A* **2016**, *38*, 590–596. [CrossRef]
16. Ramos, A.; Monteiro, E.; Silva, V.; Rouboa, A. Co-gasification and recent developments on waste-to-energy conversion: A review. *Renew. Sustain. Energy Rev.* **2018**, *81*, 380–398. [CrossRef]
17. Asam, Z.U.Z.; Poulsen, T.G.; Nizami, A.-S.; Rafique, R.; Kiely, G.; Murphy, J.D. How can we improve biomethane production per unit of feedstock in biogas plants? *Appl. Energy* **2011**, *88*, 2013–2018. [CrossRef]
18. Sambusiti, C.; Monlau, F.; Ficara, E.; Musatti, A.; Rollini, M.; Barakat, A.; Malpei, F. Comparison of various post-treatments for recovering methane from agricultural digestate. *Fuel Process. Technol.* **2015**, *137*, 359–365. [CrossRef]
19. Kulkarni, M.B.; Ghanegaonkar, P.M. Methane enrichment of biogas produced from floral waste: A potential energy source for rural India. *Energy Sources Part A* **2019**, *41*, 2757–2768. [CrossRef]
20. Martínez-Ruano, J.A.; Restrepo-Serna, D.L.; Carmona-Garcia, E.; Giraldo, J.A.P.; Aroca, G.; Cardona, C.A. Effect of co-digestion of milk-whey and potato stem on heat and power generation using biogas as an energy vector: Techno-economic assessment. *Appl. Energy* **2019**, *241*, 504–518. [CrossRef]
21. Nzotcha, U.; Kenfack, J. Contribution of the wood-processing industry for sustainable power generation: Viability of biomass-fuelled cogeneration in Sub-Saharan Africa. *Biomass Bioenergy* **2019**, *120*, 324–331. [CrossRef]
22. Madanayake, B.N.; Gan, S.; Eastwick, C.; Ng, H.K. Biomass as an energy source in coal co-firing and its feasibility enhancement via pre-treatment techniques. *Fuel Process. Technol.* **2017**, *159*, 287–305. [CrossRef]
23. National Energy Administration (NEA). *Twelfth Five-Year Plan of Biomass Energy Development*; National Energy Administration: Beijing, China, 2012.
24. China National Renewable Energy Center (CNREC). *Renewable Energy Manual*; China National Renewable Energy Center: Beijing, China, 2016.
25. Zhao, X.L.; Cai, Q.; Li, S.J.; Ma, C.B. Public preferences for biomass electricity in China. *Renew. Sustain. Energy Rev.* **2018**, *95*, 242–253. [CrossRef]
26. Singh, J. Overview of electric power potential of surplus agricultural biomass from economic, social, environmental and technical perspective—A case study of Punjab. *Renew. Sustain. Energy Rev.* **2015**, *42*, 286–297. [CrossRef]
27. Susaeta, A.; Alavalapati, J.; Lal, P.; Matta, J.R.; Mercer, E. Assessing public preferences for forest biomass-based energy in the southern United States. *Environ. Manag.* **2010**, *45*, 697–710. [CrossRef]
28. Soliño, M.; Farizo, B.A.; Vázquez, M.X.; Prada, A. Generating electricity with forest biomass: Consistency and payment timeframe effects in choice experiments. *Energy Policy* **2012**, *41*, 798–806. [CrossRef]
29. Kosenius, A.K.; Ollikainen, M. Valuation of environmental and societal trade-offs of renewable energy sources. *Energy Policy* **2013**, *62*, 1148–1156. [CrossRef]
30. Karacan, C.Ö.; Ruiz, F.A.; Cotè, M.; Phipps, S. Coal mine methane: A review of capture and utilization practices with benefits to mining safety and to greenhouse gas reduction. *Int. J. Coal Geol.* **2011**, *86*, 121–156. [CrossRef]
31. Moore, T.A. Coalbed methane: A review. *Int. J. Coal Geol.* **2012**, *101*, 36–81. [CrossRef]
32. Zhou, F.B.; Xia, T.Q.; Wang, X.X.; Zhang, Y.F.; Sun, Y.N.; Liu, J.S. Recent developments in coal mine methane extraction and utilization in China: A review. *J. Nat. Gas Sci. Eng.* **2016**, *31*, 437–458. [CrossRef]
33. Cheng, Y.P.; Wang, L.; Zhang, X.L. Environmental impact of coal mine methane emissions and responding strategies in China. *Int. J. Greenh. Gas Control.* **2011**, *5*, 157–166. [CrossRef]
34. Karakurt, I.; Aydin, G.; Aydiner, K. Mine ventilation air methane as a sustainable energy source. *Renew. Sustain. Energy Rev.* **2011**, *15*, 1042–1049. [CrossRef]
35. Weldemichael, Y.; Assefa, G. Assessing the energy production and GHG (greenhouse gas) emissions mitigation potential of biomass resources for Alberta. *J. Clean. Prod.* **2016**, *112*, 4257–4264. [CrossRef]
36. Feng, D.D.; Wang, S.Z.; Zhang, Y.; Zhao, Y.J.; Sun, S.Z.; Chang, G.Z.; Lai, X.Y.; Tan, H.P.; Qin, Y.K. Review of Carbon Fixation Evaluation and Emission Reduction Effectiveness for Biochar in China. *Energy Fuels* **2020**, *34*, 10583–10606. [CrossRef]
37. Alatzas, S.; Moustakas, K.; Malamis, D.; Vakalis, S. Biomass Potential from Agricultural Waste for Energetic Utilization in Greece. *Energies* **2019**, *12*, 1095. [CrossRef]
38. Yang, Y.; Wu, Y.J.; Liu, H.Q.; Ribeiro, A.M.; Li, P.; Yu, J.G.; Rodrigues, A.E. Enrichment of ventilation air methane by adsorption with displacement chromatography technology: Experiment and numerical simulation. *Chem. Eng. Sci.* **2016**, *149*, 215–228. [CrossRef]
39. Rao, P.V.; Baral, S.S.; Dey, R.; Mutnuri, S. Biogas generation potential by anaerobic digestion for sustainable energy development in India. *Renew. Sustain. Energy Rev.* **2010**, *14*, 2086–2094. [CrossRef]
40. Nikkhah, A.; Bagheri, I.; Psomopoulos, C.; Payman, S.H.; Zareiforoush, H.; El Haj Assad, M.; Bakhshipour, A.; Ghnimi, S. Sustainable second-generation biofuel production potential in a developing country case study. *Energy Sources Part A* **2019**, 1–14. [CrossRef]

41. Zhang, L.; Hu, Y.; Cai, L.; Kung, C.-C. A review of economic and environmental consequences from waste-based power generation: Evidence from Taiwan. *Energy Explor. Exploit.* **2020**, *39*, 571–589. [CrossRef]
42. Seglah, P.A.; Wang, Y.J.; Wang, H.Y.; Bi, Y.Y. Estimation and efficient utilization of straw resources in Ghana. *Sustainability* **2019**, *11*, 4172. [CrossRef]
43. Braun, R.; Wellinger, A. Potential of Co-Digestion. IEA Bioenergy.37. 2003. Available online: https://www.ieabioenergy.com/blog/publications/iea-bioenergy-strategic-plan-2003-2006/ (accessed on 11 January 2022).
44. Kang, J.; Li, J.P.; Zhen, X.F.; Osman, Y.I.A.; Feng, R.; Si, Z.T. Experimental study on productivity performance of household combined thermal power and biogas system in northwest China. *BioMed. Res. Int.* **2018**, *2018*, 7420656. [CrossRef]
45. Wang, Y.J.; Bi, Y.Y.; Gao, C.Y. The assessment and utilization of straw resources in China. *Agric. Sci. Chin.* **2010**, *9*, 1807–1815. [CrossRef]
46. IPCC. *2019 Refinement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories; Kyoto, Japan*. Available online: https://www.ipcc.ch/report/2019-refinement-to-the-2006-ipcc-guidelines-for-national-greenhouse-gas-inventories/ (accessed on 12 May 2019).
47. Singh, A.K.; Sahu, J.N. Coal mine gas: A new fuel utilization technique for India. *Int. J. Green Energy* **2018**, *15*, 732–743. [CrossRef]
48. Cluff, D.L.; Kennedy, G.A.; Bennett, J.G.; Foster, P.J. Capturing energy from ventilation air methane a preliminary design for a new approach. *Appl. Therm. Eng.* **2015**, *90*, 1151–1163. [CrossRef]
49. Burnete, N.V.; Mariasiu, F.; Depcik, C.; Barabas, I.; Moldovanu, D. Review of thermoelectric generation for internal combustion engine waste heat recovery. *Prog. Energy Combust. Sci.* **2022**, *91*, 101009. [CrossRef]
50. IPCC Guidelines for National Greenhouse Gas Inventories, Volume 2. Energy. (Chapter 4): Fugitive Emissions. Intergovernmental Panel on Climate Change. 2006. Available online: http://www.ipccnggip.iges.or.jp/public/2006gl/pdf/2_Volume2/V2_4_Ch4_Fugitive_Emissions.pdf (accessed on 14 April 2020).
51. Tomislav, P.; Paul, L.; Aoife, F.; Natasa, M.; Neven, D. Sustainable development of energy, water and environment systems. *Renew. Sust. Energy Rev.* **2018**, *82*, 1685–1690. [CrossRef]