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Greenhouse gas emissions of a biomass-based pyrolysis plant in China

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ABSTRACT

Biomass pyrolysis offers an alternative to industrial coal-fired boilers and utilizes low temperature and long residence time to produce syngas, bio-oil and biochar. Construction of biomass-based pyrolysis plants has recently been on the rise in rural China necessitating research into the greenhouse gas emission levels produced as a result. Greenhouse gas emission intensity of a typical biomass fixed-bed pyrolysis plant in China is calculated as 1.55E−02 kg CO_2-eq/MJ. Carbon cycle of the whole process was investigated and found that if 41.02% of the biochar returns to the field, net greenhouse gas emission is zero indicating the whole carbon cycle may be renewable. A biomass pyrolysis scenario analysis was also conducted to assess exhaust production, transportation distance and the electricity-generation structure for background information applied in the formulation of national policy.

Contents

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1. Introduction

As a large agricultural country, China produces more than 800 million t of crop straws every year [1], with 80% potentially utilizable as an energy resource [2]. High value energy forms derived from biomass conversion have been recently recognized and highlighted by the Chinese government as a significant resource. Priority was established by the government in the Chinese "12th Five-Year" Planning [3] for the integration of agricultural residuals into energy production technology, specifically through the development of biomass power generation, biomass liquid fuel, biogas and briquettes fuel. Implementation of biomass energy development priorities soon followed as regulations were established by the government in 2006 allowing for subsidization of electricity produced from biomass at 0.25 yuan/kW [4]. Regulations implemented in 2008 by the Ministry of Finance and State Administration of Taxation [5] provided an added-value tax for electricity, heat, bio-oil and products derived from agricultural residues, sludge and other wastes. Construction of comprehensive biomass facilities is occurring according to Chinese "12th Five-Year" Planning. Biomass energy facilities production will reached capacity equivalent to 50 million t of standard coal in China by the year of 2015. Total capacity of biomass power is expected to reach 13 GW, while electricity generation from biomass will achieve 7.8E+10 kW h per year. Biogas yield will realize 22 km^3 per year and the production of biomass briquettes fuel and liquid fuel will be 10 million t per year and 5 million t per year, respectively [3].

Biomass pyrolysis thermally converts biomass feedstock into biochar, bio-oil, and syngas in the absence of air/oxygen [6]. Products generated from biomass pyrolysis offer options for alleviating greenhouse gas (GHG) emissions and for providing realistic options in mitigating coal combustion particulate matter (PM) emissions as the generated heat and electricity act to substitute for coal combustion in small-sized industrial boilers in China. Forms of biomass pyrolysis have been utilized for thousands of years in China [7]. Earthen kilns or brick kilns were utilized in early times to produce charcoal from wood through a traditional pyrolysis process [6,8]. The cycle of kiln production was inefficient and not economical, however, requiring more than 20 days with limited output resulting in only one type of coal produced [9]. Kiln charcoal production significantly contributed to environmental pollution in China [8] during the last century as gaseous and liquid byproducts from the traditional biomass kilns directly emitted into the environment without treatment. Pyrolysis technology has developed rapidly since the 1990s and various raw materials and reactors have been employed [10,11]. Advanced pyrolysis shortened production time required by applying external heating methods and the pollutants, including tar and exhausts, were separated and purified prior to emission. The advanced technology improved adaptability for raw materials, energy conversion efficiency and decreased environmental impacts. Utilization of gaseous and liquid byproducts also contributed to an improved economical efficiency [12,13]. Biomass pyrolysis product distribution relies on applied technology and reaction parameters, including residence time, heating rate, particle size and final temperature. Pyrolysis can be classified, according to these parameters, into conventional pyrolysis, fast pyrolysis and flash pyrolysis [14]. Fast pyrolysis and flash pyrolysis are characterized by high heating rates and short residence times with a high yield of bio-oil [15]. Limited application of bio-oil in China restricts the industrialization of these methods, however [7,16]. Conventional pyrolysis technologies, also referred to as the poly-generation pyrolysis system, provides high energy-conversion efficiency and economic profitability as it is characterized by low temperature and long residence time and generates three products, syngas, liquid oil and solid char [16]. Construction of several poly-generation pyrolysis plants in rural China has occurred with the support of the Chinese government and are mainly located at agricultural provinces with ability to support a capacity of 200–500 kg biomass per hour. Poly-generation pyrolysis can be classified into fixed-bed pyrolysis and moving-bed pyrolysis [6,16]. Fixed-bed pyrolysis technology, with its simple structure and low initial investment [6,16], is dominant in China. Moving-bed pyrolysis may operate continuously while maintaining higher energy conversion efficiency and a larger scale utility, but is still under research and development. Several fixed-bed poly-generation pyrolysis plants have been built in Hubei, Zhejiang, Henan and other areas in recent years, as listed in Table 1 [8,17–19]. Current environmental impact assessment, especially as related to greenhouse gas, is vital while further development of pyrolysis plants is trending toward larger scales as technology advances with governmental support.

Biomass derived energy, often guaranteed to be carbon neutral [24]. is widely accepted for potentially reducing fossil fuel use and associated GHG emissions. Research devoted to biomass gasification [25–28] and direct combustion [29,30] or co-combustion [24], has proven that biomass-based systems demonstrate enormous benefits in reduction of GHG emissions compared to coal power plants. Recent alternative biomass systems however, demonstrate a departure from ideal biomass cycles as non-renewable resources consumption may actually generate added GHG emissions. Research studying environmental impacts of biomass-based ethanol and biodiesel production systems, for example, produced results indicating increased GHG emissions [31–35]. Accurately

Table 1
Typical biomass poly-generation pyrolysis plants in China.

Location	Reference	Raw material	Scale (t/year)	Syngas (m^3/year)	Biochar (t/year)	Wood tar (t/year)	Wood vinegar (t/year)
Hubei	This study	Cotton stalk, rise husk, forestry residues	2.56E+03	5.47E+04	5.48E+02	9.13E+01	5.48E+02
Xinjiang	[20]	Cotton stalk, branch	1.50E+04	1.58E+07	4.63E+03	5.93E+01	1.20E+03
Hubei	[21]	Cotton stalk, wheat straw, rape stalk	4.84E+04	1.14E+07	1.14E+04	1.92E+03	9.52E+03
Henan	[22]	Straw	1.80E+04	1.80E+04	6.00E+03	3.00E+02	1.20E+03
Anhui	[23]	Straw	3.65E+02	4.75E+05	8.03E+01	2.92E+00	3.65E+01

determining GHG emissions produced as a result of increasingly used biomass-based systems is imperative.

Considerable debate surrounds GHG emissions generated by pyrolysis systems. Zhong et al. (2010) [36] analyzed environmental impacts of wood waste flash pyrolysis and declared that continuous research is required to further reduce global warming potential from this pyrolysis system. Cao et al. (2013) [37] compared energy and greenhouse gas emission from a fast pyrolysis system combined with anaerobic digestion and a fast pyrolysis system for bioenergy conversion. Both systems achieved GHG emission benefits with the anaerobic digestion system demonstrating a superior performance to the fast pyrolysis system. Roberts et al. (2009) [38] analyzed the net climate change impact of a slow pyrolysis system. Results indicated that net GHG emissions for late stover, early stover, and yard waste systems were negative but the switch grass pyrolysis system may act as a net GHG emitter. The carbon footprint of GHG emissions as related to biomass-based pyrolysis systems in China is still unknown. Pre-construction analysis involving GHG environmental assessments should be implemented for systems accompanied with carbon abatement plans as a pre-cursor to pyrolysis plant construction.

GHG emissions and the carbon cycle for a typical biomass pyrolysis system, a fixed-bed poly-generation pyrolysis system, in China, is investigated in this paper. GHG emissions are accounted for throughout the entire process including construction of the plant, transportation of feedstock, manufacture of equipment, operation and maintenance. The leading GHG emission point within the system is determined with results analyzed and compared to various biomass utilization technologies. Scenario analyses are then performed to optimize the biomass-based pyrolysis system. Relevant information culminates in guidance toward efforts to decrease GHG emissions resulting from Chinese biomass pyrolysis plants and provides potential governmental policy suggestions.

2. Methodology

Two principle methods are usually used for calculating GHG emissions, Input–Output Method, and Life Cycle Assessment [39]. GHG emissions of various large scales have been calculated by the Input–Output Method. Chen et al. (2011) [40] first evaluated the GHG emissions, energy, emergy and exergy consumption and other environmental factors on a global scale based on the Input–Output Method, and established the related database [41,42]. Ahmad and Wyckoff (2003) [43] evaluated GHG emissions of fossil fuels from 24 countries in 1995 according the statistics of Organization for Economic Co-operation and Development (OECD) and International Energy Agency (IEA), establishing the GHG emissions database of 14 departments. Later, Nakano et al. (2009) [44] expanded the database to 17 departments of 41 countries. Hertwich and Peter (2009) [45] researched the GHG emission of 8 departments (construction, shelter, food, clothing, manufactured products, mobility, service and trade) for 73 nations and 14 aggregate world regions. Zhou [46] analyzed the GHG emission intensity for 151 typical products within the Material Product System(MPS) and the System of National Accounts (SNA). Input–Output Method application may confirm data integrity, however, results are based on specific industry averages, and can not calculate GHG emissions for a specific biomass-based utilization systems recently due to data unavailability. Life Cycle Assessment (LCA) is often applied to determine GHG emissions of these systems, such as for the biomass-based liquid fuel production systems [31,47–58], biomass pyrolysis systems [7,36,38,59,60], biomass gasification systems [25,27,28,61]. Börjesson et al. (2009) [62] emphasized that definition of the system boundary may bear enormous effects on final results. Johnson (2008) [63] calculated GHG emissions of liquefied petroleum gas(LPG) and electric forklifts according to several typical and distinct carbon footprint system boundaries, and suggested that definition of system boundary should be sensible and transparent, but not prescribed. In theory, it is impossible to avoid the definition of system boundary only by life cycle assessment, and different system boundaries will lead to incomparable of results.

Input–Output Method and LCA are combined in this study to quantify GHG (including CO_2, CH_4 and N_2O) emissions of the biomass-based pyrolysis system. The Input–Output Method acts to ensure integrity of analysis, while LCA calculates individual system component GHG emissions. Thus the traditional LCA, which is a chain accounting, has been extended into a net-based calculation, which has been already used to evaluate the GHG of Chinese wind farm and solar tower [34,64–67]. Meanwhile, the GHG associated with equipment manufacture, building materials production and waste treatment are usually ignored in previous study under different system boundary definitions due to data unavailability. In this study, these can be accounted and considered in a scientific way by combining the Input–Output Method with LCA. Thus for the first time the whole picture of GHG emissions for a biomass pyrolysis system can be nearly revealed.

Calculations of GHG emissions include the collection and transportation of biomass raw materials and the construction of the plant and biomass pyrolysis processes. Cultivation processes of biomass feedstock are precluded as raw materials of the plant consist of biomass residues, byproducts from the agricultural industries, thus production of the biomass residues would not increase environmental pressure [68]. System GHG emissions generally consist partially of direct emissions and partially of indirect emissions [69,70]. Direct GHG emissions, the GHG released due to combustion of syngas, biochar and wood tar, are assumed as net zero since the GHG released is captured by photosynthesis in the biomass growth process. Greenhouse gas is discharged indirectly as a result of activities such as the construction of buildings, the manufacture of equipment, the generation of electricity etc. The carbon cycle encompassing the entire system is illustrated in Fig. 1.

An inventory of all input material flows into the total chain of processes is listed as a first step in calculating GHG emissions [34]. GHG emissions associated with nonrenewable energy costs can then be calculated as input flows multiplied by suitable conversion coefficients which express the unit GHG emissions of each input [64].

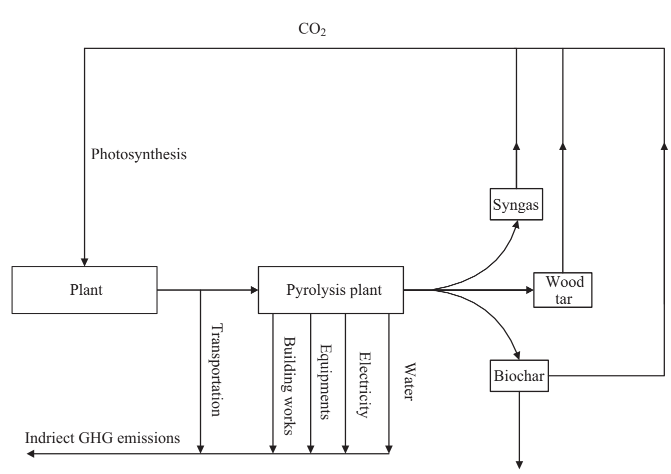
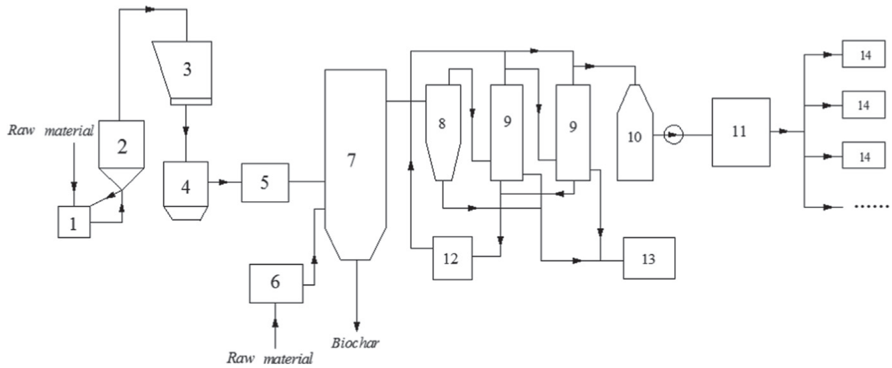


Fig. 1. Carbon cycle of the whole processes.



1—Shredder 2—Separator 3—Filler silo 4—Dryer 5—Molding machine

6—Heating furnace 7—Retort 8—Separating tower 9—Cooling tower

10—Filtering tower 11—Gasholder 12—Wood vinegar storage pool

13—Wood tar storage pool 14—User

Fig. 2. The diagram of a biomass-based pyrolysis plant in China.

GHG emission intensity (EI) is defined as the amount of GHG generated by one unit output energy of the system [66], expressed as

$$EI = \frac{GHG}{E_{out}}$$

where GHG is the GHG emission directly and indirectly in the production process and E_{out} is the energy content of the product.

The GHG emissions can be calculated as

$$GHG = \sum GHG_i = \sum (Input_i \times G_i)$$

where GHG_i denotes the GHG emissions directly and indirectly in the production of the ith inputs to the whole processes of a biomass-based pyrolysis plant, G_i is defined as the GHG-intensity coefficient of the ith inputs [65]. In this study, most GHG-intensity coefficients associated with GHG emissions can be found in Zhou [46].

Quantification of GHG emissions of all processes is possible utilizing this method. Some GHG emissions are exclusive in our study due to data inaccessibility such as: (1) GHG emissions from plant wastewater treatment; (2) Labor and machines GHG emissions during construction of the plant.

3. Inventory of the biomass-based pyrolysis plant

Study focus is based on a biomass-based pyrolysis plant located in Tianmen, Hubei Province, China, with a coverage area of 18,000 m^2 and a calculated operational life of 20 years.

The general plant diagram is illustrated in Fig. 2 with research outputs listed in Table 2.

Fixed-bed pyrolysis is a promising energy-conversion technology with three products, syngas, bio-oil and biochar. Syngas is utilizable as a combustion fuel following purification [71] and is mainly composed of H_2, CH_4, CO and CO_2 with a yield of 547,500 m^3 per year and a low heating value of 12.1 MJ/m^3. Absence of oxygen during the pyrolysis process leads to high content of methane (40% of syngas) and hydrogen (10% of syngas), the principle contributors to heating value, resulting in syngas obtained by fixed-bed pyrolysis retaining higher heating value than syngas obtained from gasification. Biochar represents 25–30% of total plant products, producing a total weight of 547.5 t annually. Biochar retains high stable carbon content with the potential to offset GHG emission [72]. Wood tar, the main content

Table 2
The outputs of the plant.

Outputs	Energy (MJ)	Percentage (%)
Syngas	1.33E+08	25.36
Biochar	3.39E+08	64.75
Wood tar	5.18E+07	9.90
Total	5.24E+08	100.00

of liquid products, is produced annually at a rate of 91.25 t. Chemical processes allow conversion of wood tar into biodiesel. Wood vinegar is an additional liquid product generated and is mainly composed of water and acetic acid. Wood vinegar is not considered in this study as it retains a high water content (over than 85%) and low heating value.

Four major components of plant performance were studied:

(1) Building works (combination workshop and office buildings);
(2) Equipment (drying and molding system, pyrolysis carbonization system and separation and purification system);
(3) Transportation;
(4) Operation and maintenance.

3.1. Building works

Combination workshop and office buildings construction are analyzed under the building works component of the plant performance study. The combination workshop includes workshops for drying and molding, pyrolysis carbonization, separation and purification and also includes the wood tar storage pool, wood vinegar storage pool and circulating water pool. Construction materials of building works consist of bricks total weight of 777.68 t, concrete volume of 234.11 m^3, and steel total weight of 35.1 t. The total GHG emissions of building works can be calculated as 5.85E+02 t CO_2-eq. The data of building works for other biomass pyrolysis plants are unavailable, as these research published did not describe the data associated with building works. Thus the GHG emissions of other biomass-based thermal conversion systems with available data are evaluated in this study to compare with the studied system as shown in Table 3. It is note that data of the 20 MW integrated biomass gasification combined cycle plant

Table 3
GHG emissions of biomass thermal conversion systems caused by building works.

Cases	Location	Building materials	GHG emission (t CO_2-eq)
Biomass pyrolysis system (this study)	China	Concrete, steel, brick	5.82E+02
20 MW integrated biomass gasification combined cycle plant [73]	China	Cement, steel, iron, aluminum	1.50E+03
15 MW biomass direct combustion heat and power plant [74]	China	Concrete, steel, brick	5.18E+03

Table 4
Energy consumption of different transportation modes.

Number	Mode of transportation	Power sources	Consumption intensity	Unit	Density (kg/L)
1	Highway	Diesel	0.050 [77]	L/(t km)	0.83
2	Highway	Gasoline	0.080 [78]	L/(t km)	0.75
3	Railway	Electricity	0.016 [79]	kW h/(t km)	–
4	Railway	Diesel	0.025 [77]	L/(t km)	0.83

and of the 15 MW biomass direct combustion heat and power plant are from our previous research [73]. Building works depends on the scale of workshops, office buildings and auxiliary constructions. GHG emissions of the biomass gasification system caused by building works are lower that of the biomass direct combustion system. And GHG emissions of the studied system are lower than that of the other systems listed in Table 3, because compared with the studied system, the other systems include extra building works associated with electricity generation processes.

3.2. Equipment

3.2.1. Drying and molding system

The drying and molding system includes machines to shred, dry and mold. Raw material is first placed in a shredder and processed into particles approximately 2 mm in size [75]. A drying process is then applied to decrease moisture content of the raw material particles as a dried biomass feedstock will increase pyrolysis efficiency. Biomass feedstock moisture content levels must adhere to limits as extremely dried feedstock may increase reaction temperature leading to the formation of contaminants such as nitrogen oxides (NO_x) [76]. The moisture content of the raw material particles in this study is approximately 8–12%. Subsequently, the small biomass particles will be extruded in a molding machine to form biomass briquettes with density no less than 1000 kg/m^3.

3.2.2. Pyrolysis carbonization system

The pyrolysis carbonization system consists of two heating furnaces and five retorts. Diameter of a pyrolysis retort is approximately 1.6–2.2 m. Pyrolysis of crop straws is divided into four stages: drying stage, pre-carbonization stage, carbonization stage and calcination stage. Reaction temperature in the drying stage is kept below 120–150 °C with low heating rate while moisture in the crop straws evaporates with virtually no conversion of chemical composition. Pre-carbonization stage reaction temperature is maintained at 150–275 °C while volatile components decomposition produces carbon dioxide, carbon monoxide and acetic acid. The carbonization stage, the central process of pyrolysis, maintains higher reaction temperatures at approximately 275–450 °C, resulting in higher liquid yield (wood tar and wood vinegar) and lower biochar production [7]. Calcination is the final pyrolysis stage and retains an integral role in the process of upgrading biochar quality with temperature maintained between 450 and 500 °C.

3.2.3. Separation and purification system

Separating tower, cooling tower and filter tower constitute the separation and purification system. This system functions to provide cooling and impurity removal, including gas–liquid separation, removal of acid gas and tar ash. Wood vinegar steam is converted to liquid by the cooling tower and utilized in the system as cooling water as illustrated in Fig. 2.

GHG emissions caused by equipment can be calculated as 2.7E+02 t CO_2-eq. Data of equipment list of other biomass pyrolysis systems is unavailable. Nevertheless detailed data of a Chinese biomass direct combustion system [74] and a Chinese biomass gasification system [73] are available as we have previously studied. The equipments of 15 MW biomass direct combustion heat and power plant consist of boiler, turbine, generator, fan, pump, heater, deaerator, valve, shredder, belt conveyer and so on. GHG emissions of this direct combustion caused by equipments are 3.13E+04 t CO_2-eq. And equipments of 20 MW integrated biomass gasification combined cycle plant mainly contains gasification furnace, decontamination system, combustion engine, exhaust-heat boiler, screw expander, generator, storage system, total GHG emissions are 4.15E+02 t CO_2-eq. GHG emissions caused by equipments depend on the scale of plant, biomass utilization technology, target products and so on. Similar with the results of GHG emissions caused by building works, GHG emissions of biomass gasification system caused by equipments are lower than that of biomass direct combustion system. And because there are no electricity generation equipments in the studied biomass pyrolysis system, GHG emissions of the studied system caused by equipment are lower than that of the biomass gasification system.

3.3. Transportation

The planting area for cotton and rice is Chinese 25,000 mu and 40,000 Chinese mu. Statistics indicate the total yield of crop straw is 8000 t per year. Fossil fuel consumption for crop straw transportation from collection stations to the pyrolysis plant assumed highway transport by diesel vehicles with an average transport distance of 20 km. Diesel consumption for transportation purposes was calculated at 2.12 t per year with a plant crop straw consumption of 2555 t per year and consumption intensity of the diesel estimated at 0.05 L/(t km) [34] and diesel density at 0.83 kg/L. and diesel density at 0.83 kg/L. The GHG emission of transportation processes can be calculated as 1.91E+01 t CO_2-eq. However, different transportation modes could lead to different GHG emissions. It is note that highway is primary transportation mode in China in biomass feedstock transport industry. The power sources and consumption intensity of highway and railway transportation are listed in Table 4. GHG emissions of different transportation are shown in Fig. 3, railway transportation which consumes electricity releases least greenhouse gas. GHG emissions of highway transportation are higher than that of railway transportation, but highway transportation is more flexible, and highway transportation is highly developed in China. In addition, the biomass-based projects are usually not far from agriculture field in China; and the collection radius is usually less than 50 km, thus highway transportation is widely used in biomass feedstock transportation in

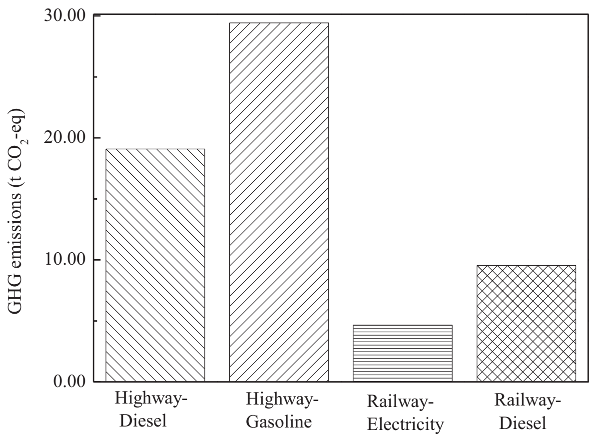


Fig. 3. GHG emissions of different transportation modes.

Table 5
GHG emissions of biomass thermal conversion systems caused by operation and maintenance.

Cases	Location	GHG emission (t CO_2-eq)
Biomass pyrolysis system(this study)	China	7.25E+03
Biomass pyrolysis for transportation fuels [80]	Spain	2.00E+03
25 MW biomass direct combustion power plant [81]	China	2.43E+03
15 MW biomass direct combustion heat and power plant [74]	China	7.60E+02
5.5 MW biomass gasification power plant [82]	China	6.83E+01

China. Energy efficiency of diesel vehicles is higher than that of gasoline vehicles, and GHG emissions of diesel vehicles are lower. Thus highway transportation by diesel vehicle is often chosen in biomass feedstock transportation.

3.4. Operation and maintenance

Operation and maintenance process consumption includes electricity and water. Electricity consumption of the drying and molding system, pyrolysis carbonization system, and separation and purification was 3.66E+05 kW h/year, 2.42E+04 kW h/year, 5.09E+04 kW h/year, respectively. The auxiliary system and domestic electricity consumption was 8.44E+04 kW h/year. Total electricity consumption of the plant was then calculated to be 5.26E+05 kW h/year. Water consumption of the circulating cooling water was consumed at 1108 t per day; chemical feed water at 415 t per day; auxiliary cooling water at 385 t per day; and 13 employees daily plant water consumption at 3.5 kg per day. Thus, the total GHG emissions of operation and maintenance are calculated as 7.25E+03 t CO_2-eq. As listed in Table 5, GHG emissions caused by operation and maintenance of other biomass thermal conversion systems are all lower than pyrolysis system. That is because the products of other biomass thermal conversion systems as shown in Table 5 are electricity or heat combined with electricity, and the operation and maintenance processes will consume the electricity generated by themselves. Thus their GHG emissions of operation and maintenance mainly induced by consumption of water, and the larger scale the system is, the more greenhouse gas the system releases.

Table 6
GHG emissions of the biomass-based pyrolysis plant.

Item	Material	Quantity	Unit	GHG intensity (t CO_2-eq/unit)	GHG (t CO_2-eq)
Building works					
Combination workshop					
Room	Brick	2.54E+02	t	5.30E−01	1.35E+02
Foundation	Concrete	1.23E+02	m^3	5.30E−01	6.52E+01
	Steel	1.84E+01	t	1.39E+00	2.56E+01
Office building					
Room	Brick	5.23E+02	t	5.30E−01	2.77E+02
Foundation	Concrete	1.11E+02	m^3	5.30E−01	5.89E+01
	Steel	1.67E+01	t	1.39E+00	2.32E+01
Equipment					
Retort	Steel	9.25E+00	t	1.39E+00	1.29E+01
Shredder		1.00E+00	t	4.75E+00	4.75E+00
Loader–unloader	Steel	8.10E−01	t	1.39E+00	1.13E+00
Crane		1.00E+01	t	4.25E+00	4.25E+01
Conveyor		5.00E−01	t	3.32E+00	1.66E+00
Molding machine		3.20E+00	t	4.75E+00	1.52E+01
Fume extractor		3.00E−02	t	4.75E+00	1.43E−01
Roots blower		1.32E−01	t	4.75E+00	6.27E−01
Submersible pump		5.00E−02	t	4.75E+00	2.38E−01
Chimney	Steel	6.00E−02	t	1.39E+00	8.34E−02
Water pump		1.00E−01	t	4.75E+00	4.75E−01
Alkali vinegar pump		2.00E−01	t	4.75E+00	9.50E−01
Generators	Silica	6.60E−04	t	6.00E−01	3.96E−04
	Copper	7.29E−03	t	4.70E+00	3.43E−02
	Steel	8.80E−02	t	1.39E+00	1.22E−01
Draught fan		1.50E−01	t	4.75E+00	7.13E−01
Thermometry box		1.00E−01	t	4.75E+00	4.75E−01
Primary separator	Steel	3.00E−01	t	1.39E+00	4.17E−01
Primary cooling separator	Steel	1.07E+00	t	1.39E+00	1.48E+00
Secondary cooling separator	Steel	6.60E−01	t	1.39E+00	9.17E−01
Comprehensive separator	Steel	5.40E−01	t	1.39E+00	7.51E−01
Gas–liquid separator	Steel	5.00E−01	t	1.39E+00	6.95E−01
	Steel	5.00E−01	t	1.39E+00	6.95E−01
Separating tower	Steel	7.50E−01	t	1.39E+00	1.04E+00
Oil–water separation tank	Steel	2.00E−01	t	1.39E+00	2.78E−01
U-tank	Steel	2.00E−02	t	1.39E+00	2.78E−02
Alkali tank	Steel	1.25E−01	t	1.39E+00	1.74E−01
Lye tank	Steel	4.00E−02	t	1.39E+00	5.56E−02
Water seal	Steel	1.20E−01	t	1.39E+00	1.67E−01
Gasholder	Steel	6.20E+01	t	1.39E+00	8.62E+01
Plates 3700*1850*10	Steel	1.29E+01	t	1.39E+00	1.79E+01
Plates 3700*1850*8	Steel	1.03E+01	t	1.39E+00	1.43E+01
Plates 3700*1850*6	Steel	2.33E+01	t	1.39E+00	3.23E+01
Shore $L=1200$	Steel	4.03E+00	t	1.39E+00	5.60E+00
Others	Steel	1.15E+01	t	1.39E+00	1.60E+01
Parallel					
Riffled plate	Steel	1.20E+00	t	1.39E+00	1.67E+00
U-Steel 12.6	Steel	4.70E+00	t	1.39E+00	6.53E+00
Round steel 108*2.5	Steel	5.60E−01	t	1.39E+00	7.78E−01
Fan frame	Steel	1.20E−01	t	1.39E+00	1.67E−01
Fan seal	Steel	1.20E−01	t	1.39E+00	1.67E−01
Pump frame	Steel	6.00E−02	t	1.39E+00	8.34E−02
Transportation					
	Diesel	4.24E+01	t	4.50E−01	1.91E+01
Operation and maintenance					
Electricity		1.05E+07	kW h	6.89E−04	7.25E+03
Water		1.39E+04	t	8.10E−05	1.13E+00
Total					8.12E+03

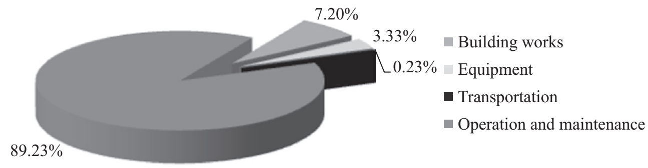


Fig. 4. GHG emissions fractions of the biomass-based pyrolysis plant.

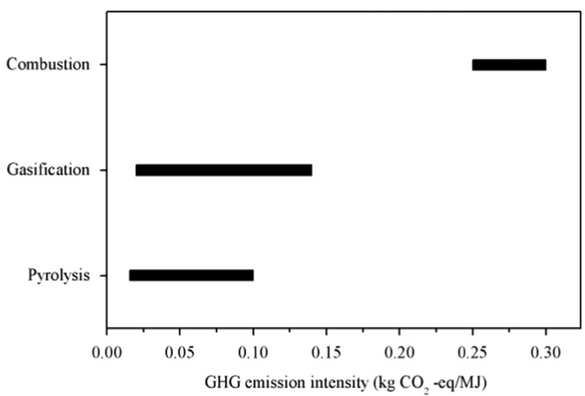


Fig. 5. GHG emission intensity comparison of different biomass thermal conversion technologies.

4. Results and discussions

4.1. Results

Biomass-based pyrolysis plant life cycle GHG emissions are listed in Table 6.

Total calculated GHG emissions for the analyzed Tianmen, Hubei Province biomass-based pyrolysis plant is 8.12E+03 t CO_2-eq. E_{out} of the plant is 5.24E+08 MJ, as listed in Table 2. Thus, GHG emission intensity is calculated to be 1.55E–02 kg CO_2-eq/MJ, indicating the plant emits 1.55E–02 kg GHG to generate 1 MJ of energy. Analysis of Table 3 results indicate the operation and maintenance process as the largest contributor to total GHG emissions with 89.23% of total plant GHG emissions. Fig. 4 demonstrates that building works contribute 7.20% to overall GHG emissions while the equipment manufacturing process contributes 3.33%. Transportation process GHG emissions are insignificant (0.23%). Electricity accounts for the highest consumption in the operation and maintenance process due to use of fossil fuels in the electricity generation process. Reduction in electricity consumption would function to decrease GHG emissions.

GHG emission intensity is an integral parameter utilized to measure environmental impacts of the system. GHG emission intensity of various biomass derived thermal conversion technologies are compared and presented in Fig. 5. GHG emission intensities of the biomass combustion system (0.25–0.30 kg CO_2-eq/MJ) are much higher than the pyrolysis system [83–85]. The GHG emission intensities of the biomass gasification system range from 0.02 to 0.14 kg CO_2-eq/MJ [86–88] and 0.012–0.1 kg CO_2-eq/MJ for the biomass pyrolysis system [89–91], while both are renewable technologies and retain benefits to reduce GHG emissions. Compared with other biomass derived thermal conversion technologies, however, the fixed-bed pyrolysis technology demonstrates a significant benefit in GHG reduction as its GHG emission intensity is relatively low (0.0155 kg CO_2-eq/MJ in this study).

GHG emission intensities of different biomass pyrolysis systems are reviewed and listed in Table 7. The differences of system scales, target products, feedstock, calculation methods lead to different results. The GHG emission intensity of this study approximated to

Table 7
GHG emission intensity of different biomass pyrolysis system.

Location	Year of study	Items	EI (kg CO_2-eq/MJ)
China	2012	Biomass pyrolysis system(this study)	0.016
USA	2008	Biomass pyrolysis system for biochar production [92]	0.025
Germany	2008	Biomass fast pyrolysis for liquid fuels [91]	0.070
USA	2010	Biomass for oil and electricity generation [93]	0.012
China	2014	Bio-fuel production via fast pyrolysis of corn stover [94]	0.029

that of biomass pyrolysis systems listed in Table 7, except for biomass fast pyrolysis system for liquid fuels in Germany. This is because the pyrolysis system in Germany is not a commercial plant and the energy conversion efficiency is relatively low. The biomass poly-generation pyrolysis system studied converts biomass to syngas, bio-oil and biochar, the energy efficiency is enhanced compared with other pyrolysis systems with a single product, thus the studied system may released less greenhouse gas when delivering the same amount of energy into society.

The biomass pyrolysis system acts as a substitute for industrial boilers that combust coal. Presently, the national average GHG emission intensity of coal power plants is 0.22 kg CO_2-eq/MJ [65]. The coal power plant produces approximately 14.2 times more GHG emissions than the biomass-based pyrolysis plant per unit energy output.

4.2. Carbon cycle of the whole processes

4.2.1. Carbon balance

Carbon balance would be achievable if indirect GHG emissions were not accounted for as revealed in Fig. 1 (Section 2). Annual consumption of raw materials is approximately 2555 t while carbon content of the raw materials is approximately 845.16 t and product carbon content is approximately 632.89 t. Total carbon content in raw materials is greater than in products as raw materials are burned directly in the heating furnace to heat the pyrolysis retort, emitting approximately 180 t carbon directly into the atmosphere. Additionally, as loss occurs in transportation, modeling and carbonization, portions of carbon are released but not converted into products.

The carbon cycle becomes imbalanced due to utilization of carbon-driven inputs, such as electricity from coal-fired power plant, diesel from raw oil, equipment and buildings. Net carbon emissions, as previously calculated, were 1.55E−02 kg CO_2-eq/MJ for the Tianmen, Hubei Province plant, indicating extra 1.55E−02 kg CO_2-eq was emitted into the atmosphere outside of the carbon cycle per MJ energy produced. Carbon emission levels indicate the cycle is nonrenewable in this case.

4.2.2. Biochar returning

Significant greenhouse gas reduction is possible through implementation of biochar as a carbon storage mechanism. Carbon storage through biochar content in soil is feasible and biochar is viewed as a sound option for atmospheric carbon sequestration when returned to the field [95]. Characteristics of biochar include exceptional stability chemically, thermally and microbiologically [96]. Debate prevails however regarding residence time and the stability of biochar in soil [97,98]. Debate prevails however regarding residence time and the stability of biochar in soil [99–101]. Another perspective views biochar as not acting as a permanent carbon sink as, although carbon may be biochar-fixed in

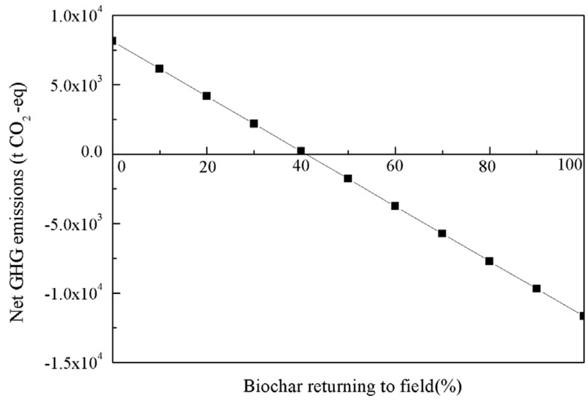


Fig. 6. GHG emissions of different percentage of biochar returning to the field.

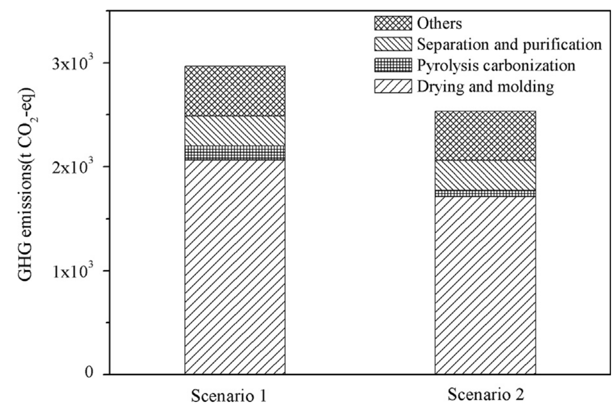


Fig. 7. GHG emissions of different scenario.

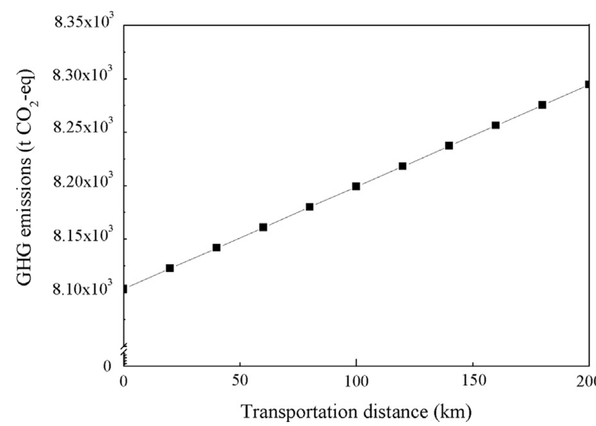


Fig. 8. GHG emissions of different transportation distance.

soil for thousands of years, oxidation or absorption of soil organic matter will eventually alter characteristics of biochar in the soil [102,103].

Sustainable development practices are beginning to consider the return of biochar to the field as a practical method in GHG emissions mitigation. In this study, it is assumed that 30% of the carbon emits into the atmosphere and 70% fixes in the soil [104,105]. The Tianmen, Hubei Province plant produces 1.10E+04 t biochar for 20 years, if all biochar produced is returned to the field, net GHG emission of the system would be −3.20E+04 t CO_2-eq, and GHG emission intensity would be −6.11E−02 kg CO_2-eq/MJ, indicating greater GHG is reduced than emitted. Various percentages of biochar may lead to different reductions in GHG emission, as presented in Fig. 6. Net GHG emission is zero when 41.02% of the biochar is returned to the field, indicating the whole carbon cycle may be renewable. Production of biochar through biomass pyrolysis with returns of biochar to fix carbon in the field should receive governmental support as a method to mitigate GHG emissions.

4.3. Scenario analysis

Several scenario analyses were conducted to optimize the fixed-bed pyrolysis system.

4.3.1. Utilization of exhaust

The current status of the plant, considered as scenario 1 (base case scenario) and another scenario are evaluated in this section. According to the analysis results in Section 4.1, high electricity consumption is the main factor affecting total GHG emissions. Electricity consumption of the plant occurs during the following processes: drying and molding, pyrolysis carbonization, separation and purification and others with the drying and modeling process responsible for 70% of the total. Reduction of electricity consumption produced by the system is necessary as energy saving and emission reduction is a long-term plan established within Chinese economic and social development policy [106,107]. Scenario 1 reflects current GHG emissions generated by the electricity consumption of each process. Scenario 2 substitutes high temperature exhaust for the heating furnaces and dryer to decrease GHG emissions caused by electricity consumption. Exhaust utilized to dry the biomass feedstock and heat the retorts will reduce electricity consumption of the drying and molding process, decreasing pyrolysis carbonization and leading to a 14.52% GHG reduction, as presented in Fig. 7. Exhaust utilization technology should be further researched for improvement and application by reviewing both domestic and foreign advance technology methods and management. Governmental incentives through financial and tax policies may succeed in supporting utilization of exhaust in the biomass poly-generation pyrolysis system.

4.3.2. Transportation distance

Biomass transportation is a significant component in GHG emissions calculations with several studies focused on variability in overall contributions. Research is dominated by studies focused on economical impact of purchased biomass costs while only a few studies have focused on GHG emissions as related to the biomass feedstock transportation process. Xing et al. (2008) [108] built mathematical models to simulate the collection cost, energy consumption and environmental pollution of biomass collection and transportation processes. Results indicate that collection costs of biomass are proportional to transportation distance, transportation fuel consumption and distance. Caputo et al. (2005) [109] analyzed the economics of biomass-based power plants. Results reveal that higher vehicle transport costs, lower vehicles capacity, higher biomass purchase costs and lower distribution density lead to a decrease in economic benefits.

Effects of biomass transportation on GHG emissions are investigated, in this section, through viewing a range of highway distances to the biomass-based pyrolysis plant by diesel vehicles. Fig. 8 presents five points of transportation distance, increasing from 0 to 200 km. As the transportation distance increases, the GHG emissions increase from 8.10E+03 to 8.29E+03 t CO_2-eq, leading to a 2.34% GHG emission increase. Thus the influences of transportation on total GHG emission of biomass-based pyrolysis plant are not obvious. The collection radius could be expanded to collect more feedstocks and enlarge the scale of plant.

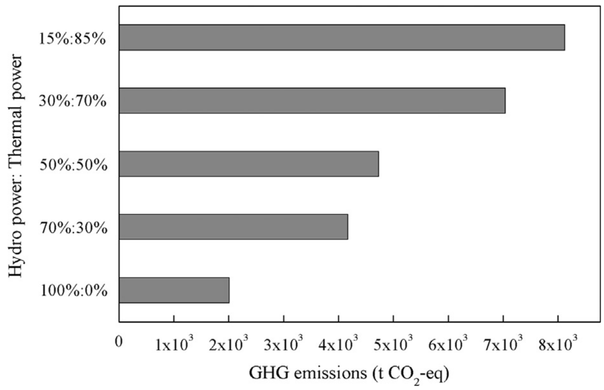


Fig. 9. GHG emissions with different electricity generation structures.

4.3.3. Electricity-generation structure

Biomass-based fixed-bed pyrolysis plant electricity consumption offers a disadvantage as GHG emissions are increased with high electricity consumption. Contributions from the dominating coal combustion electricity production already have induced an elevated GHG emission status. GHG emission intensity comparisons in China indicate thermal power produces 0.22 kg CO_2-eq/MJ and hydropower produces 0.03 kg CO_2-eq/MJ [34]. Assumed in this study, is that 15% of electricity generated originates from hydropower and 85% from coal-fired power, thus the GHG emission intensity of electricity is evaluated to be 0.19 kg CO_2-eq/MJ, and as previously described, the total GHG emission for this pyrolysis plant is 8.12E+03 t CO_2-eq. GHG emission intensity of various electricity generation structures can be calculated as with thermal and hydropower, enabling evaluation of total GHG emissions under diverse electricity generation structures. Comparisons are drawn between GHG emissions under different electricity-generation structures as demonstrated in Fig. 9. Results reveal that if all electricity is generated from a hydropower plant, the pyrolysis system may lead to a 75.42% GHG reduction and total GHG emissions would decrease to 2.01E+03 t CO_2-eq with GHG emission intensity reducing to 3.84E−03 kg CO_2-eq/MJ, much lower than 1.55E−02 kg CO_2-eq/MJ. Governmental policy should encourage an increase in hydropower plant construction and a decrease in the proportion of coal power plants, according to the results.

4.3.4. Agriculture process

The total cultivated area of cotton and rice is Chinese 25,000 mu and 40,000 Chinese mu. Statistics indicate the total yield of crop straw is 8000 t per year. The pyrolysis plant is able to process 2555 t biomass feedstock includes 1600 t of cotton stalk and 955 t of rice husk. According the statistical data of Chinese Ministry of Agriculture, the consumption of nitrogen fertilizer, phosphate fertilizer and potash fertilizer for every Chinese mu cotton is 12.2 kg, 5.1 kg and 4.1 kg, respectively, and for every Chinese mu rice is 10.9 kg, 4.3 kg and 2.9 kg [110]. The average consumption of pesticides is 0.097 kg every Chinese mu in China and the consumption of machines and diesel are 7.3 kg/m^2 and 15 kg/m^2 every year, respectively [111]. Raw materials of the studied pyrolysis plant are agricultural residues. In this study, the consumption of energy or material in a agriculture process is allocated according to market value of cotton and cotton stalk, rice and rice husk. The data of the studied biomass pyrolysis plant are collected and calculated in 2012, and according to the project report, the average price of biomass raw material is 200 yuan/t. In 2012, the average price of cotton and rice is 20,400 yuan/t [112] and 2500 yuan/t [113] in Hubei Province. The calculation of GHG emissions of the agriculture process for biomass pyrolysis plant are listed in Table 8. If the agriculture process is included, the GHG emission intensity of the plant will increase to 1.56E−02 kg CO_2-eq/MJ, which only increased 0.89%. Besides, GHG emissions of different raw materials in the agriculture process are shown in Fig. 10.

Table 8
GHG emissions of the agriculture process for biomass pyrolysis plant in China.

Item	Quantity	Unit	GHG intensity (t CO_2-eq/unit)	GHG (t CO_2-eq)
Nitrogen fertilizer	3.28E+01	t	1.64E+00	5.38E+01
Phosphate fertilizer	1.30E+01	t	1.05E+00	1.36E+01
Potash fertilizer	8.86E+00	t	3.00E−02	2.66E−01
Pesticides	2.90E−01	t	3.00E+00	8.71E−01
Machines	1.46E+00	t	1.39E+00	2.03E+00
Diesel	2.99E+00	t	4.50E−01	1.35E+00
Total				7.20E+01

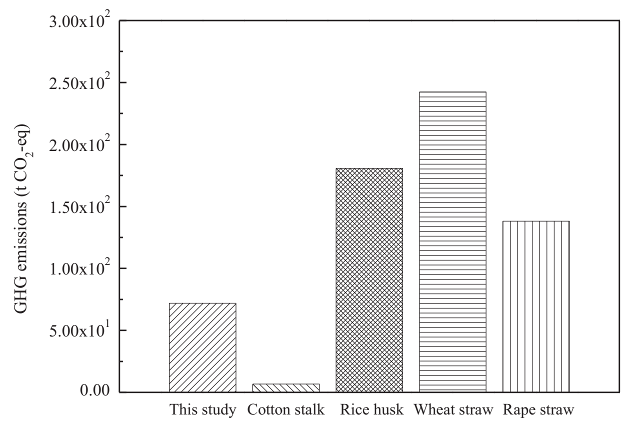


Fig. 10. GHG emissions of different raw materials in the agriculture process.

5. Conclusions

Greenhouse gas emission levels have essential implications for the biomass-based pyrolysis system and play an integral role in project design and decision making. This study focuses on the GHG emissions of the Tianmen, Hubei Province plant in China, a biomass-based pyrolysis plant generating three products, syngas, biochar and bio-oil. Production of biochar by the pyrolysis system generates a significant effect on greenhouse reduction eenhouse gas reduction [89,114,115]. The study revealed that if all generated biochar was burned for energy, the GHG emissions intensity of the studied plant would be 1.55E–02 kg CO_2-eq/MJ, a lower level among the GHG intensity spectrum of biomass thermal conversion systems. [89–91]. However, if all biochar was returned to the field, the net GHG emissions intensity would be negative, evaluated as −6.11E–02 kg CO_2-eq/MJ. According to statistics in the 12th Five-Year Plan of China, 460 million t of biomass resources were utilizable in 2010, but only 2.4 million t was consumed. According to statistics in the 12th Five-Year Plan of China, 460 million t of biomass resources were utilizable in 2010, but only 2.4 million t was consumed [3]. If half of the biomass was used for biochar production by pyrolysis, approximately 0.26 million t biochar would be produced and, assuming all biochar returns to the field, 9.43E+05 t CO_2-eq reduction would occur.

Results also indicate that GHG emissions of the studied plant primarily arise from the electricity consuming operation and maintenance process. Utilization of exhaust heat was proposed for electricity consumption reduction within the fixed-bed pyrolysis system and was found to reduce the total GHG emission by 14.52% [116]. Furthermore, due to the coal dominated electricity generation structure in China, electricity generation process is the largest contributor to the total GHG emissions [117–119]. Results indicate that if the proportion of thermal power decreases, the total GHG emissions of the system would reduce rapidly. If all electricity is generated from hydropower, the GHG emissions are 2.01E+03 t CO_2-eq, which leading to a 75.42% GHG reduction.

Additionally, analysis of transportation distance reveals that when the transportation distance increases from 0 to 200 km, GHG emissions increase from 8.10E+03 to 8.29E+03 t CO_2-eq, leading to a 2.34% GHG emission, thus increase of transportation distance places minimal effect on total GHG emissions.

Biomass-based fixed-bed pyrolysis offers potential for significant GHG reduction under optimized conditions, ultimately contributing to vital reductions in overall GHG emissions as widespread urbanization continues in China.

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