

Review

The Development Strategies and Technology Roadmap of Bioenergy for a Typical Region: A Case Study in the Beijing-Tianjin-Hebei Region in China

Xin Zhang ¹, Yun-Ze Li ^{1,2,3,*} , Ao-Bing Wang ¹, Li-Jun Gao ¹, Hui-Juan Xu ¹ and Xian-Wen Ning ⁴

¹ Advanced Research Center of Thermal and New Energy Technologies, Xingtai Polytechnic College, Xingtai 054035, China; zx_xtpc@163.com (X.Z.); wab_509@163.com (A.-B.W.); gaoli_jun@foxmail.com (L.-J.G.); xuhuijuan_xpc@163.com (H.-J.X.)

² School of Aeronautic Science and Engineering, Beihang University, Beijing 100191, China

³ Institute of Engineering Thermophysics, North China University of Water Resources and Electric Power, Zhengzhou 450045, China

⁴ Beijing Key Laboratory of Space Thermal Control Technology, Beijing Institute of Space System Engineering, Beijing 100094, China; ningxianwen@163.com

* Correspondence: liyunze@buaa.edu.cn; Tel.: +86-10-8233-8778; Fax: +86-10-8231-5350

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Abstract: The Beijing-Tianjin-Hebei region has abundant biomass resources, which are difficult to collect and thus are underutilized. However, the potential estimation of biomass energy can result in a comprehensive understanding of bioenergy resources in order to establish a technology roadmap for the region's bioenergy development. Therefore, it is essential to estimate the potential of Beijing-Tianjin-Hebei biomass resources and bioenergy utilization. In this paper, the amount of main biomass resources for possible energy use and bioenergy utilization are calculated based on a statistical data estimation method for crop residues; human, poultry, and livestock manure; and municipal solid wastes. On the basis of biomass resources and bioenergy utilization potential, the technology roadmap is established. The results show that the amount for available biomass energy use is unevenly distributed in the Beijing-Tianjin-Hebei region, and the largest amount of resources is crop residues (36.52 million tons or 18.26 million tons coal equivalent). The biogas from human, poultry, and livestock manure and densified solids from crop residue technology roadmap is suitable for the Beijing-Tianjin-Hebei region.

Keywords: biomass resources; Beijing-Tianjin-Hebei region; bioenergy potential estimation; technology roadmap; bioenergy development

1. Introduction

National economic growth is related to energy consumption, and there are many studies on the relationship between economic growth and energy consumption [1–5]. The relationship between renewable and economic growth have established bi-directional causation for 18 emerging economies [6]. Sadorsky reports that per capita income rose by 1% and renewable energy consumption increased 3.5% in the long term [6]; however, a positive unidirectional causality arose between household renewable energy consumption and GDP [7]. For example, biomass energy consumption increased by 1% and GDP increased by 0.85% in 51 African countries [8]. Therefore, the rapid development of social economy promotes the sustained growth of energy demand and consumption.

According to the Statistical Review of World Energy in 2019, we found that world primary energy consumption increased to 13.9 billion tons of oil equivalent in 2018, along with an average annual growth rate of 2.9% per year, and the consumption of oil, nature gas, and coal have increased at

the same time. What is more, nuclear energy, hydroelectricity, and renewables consumption have grown [9]. In addition, traditional fossil energy will run out in the near future, and carbon dioxide emissions are increasing year by year [10,11]. Thus, it is inevitable for countries to develop renewable energy [12–14]. The Paris Agreement Conference of Parties (COP) announced that the fossil fuel age has ended, and many countries have agreed that “to undertake rapid reductions thereafter, in accordance with the best available science, so as to achieve a balance between anthropogenic emissions by sources and removals by sinks of greenhouse gases in the second half of this century, on the basis of equity and in the context of sustainable development and efforts to eradicate poverty” derived from the COP 21 report [12]. Sustainable development goals have been highlighted by the United Nations, and the importance of renewable energy for changing the world was highlighted in goals 7 and 3 of clean energy and health [15]. China is the largest emitter of greenhouse gases (GHG) [16]; hence, China plans to reduce the GHG emissions by 40–45% by 2020 [17]. For this reason, renewable energy can be used as a clean alternative to fossil fuels and is sustainable.

As per REN21’s 2019 reported, biomass energy contributed the largest to renewable energy consumption in the global energy supply, including traditional biomass utilization. By the end of 2017, the contribution of bioenergy to final energy consumption was about 12.4%, which is about 46.0 exajoules (EJ), with modern sustainable bioenergy (excluding the traditional use of biomass) providing around half of all renewable energy in the final energy consumption [18]. The world biofuels value was estimated at 7.5 billion bbl of diesel or 60 quads for the world, which were produced from annual residue [19]. Bioenergy is carbon neutral because the carbon dioxide that is released by burning is offset by the carbon dioxide absorbed when the plant in question was grown [20,21]. Thus, bioenergy production based on biomass resources is an essential substitute for fossil energy and has attracted general attention around the world [1,2,22–25].

Based on feedstock, biofuels are classified into four categories—first, second, third, and fourth generation biofuels [26]—and biomass energy can be divided into solid, liquid, and gas [25] on the basis of the form of energy utilization in power generation, heating, and transportation [27]. We can use farm wastes, forest wastes, living wastes, and industrial wastes [28] as raw materials for biomass energy in order to reduce GHG [27]. As a result, waste is reduced and it simultaneously becomes an economic resource and provides jobs for the unemployed [25,29,30]. For example, Diamantis et al. studied the different processes of cheese whey anaerobic treatment of three systems and the final net profit of biogas production, which is especially meaningful for the biomass industry and may create economic benefit for individuals and nations [28]. Global biofuel production is on the rise—in 2018, 95 million tons oil equivalent was produced worldwide, with North America, South and Central America, and Europe contributing 39, 25, and 16 million tons oil equivalent, respectively (see Figure 1). Europe is the world’s largest producer of biomass diesel, while North America is the biggest producer of ethanol (see Figure 1b). In particular, the US is the world leader in biomass ethanol production (see Figure 1c) [31].

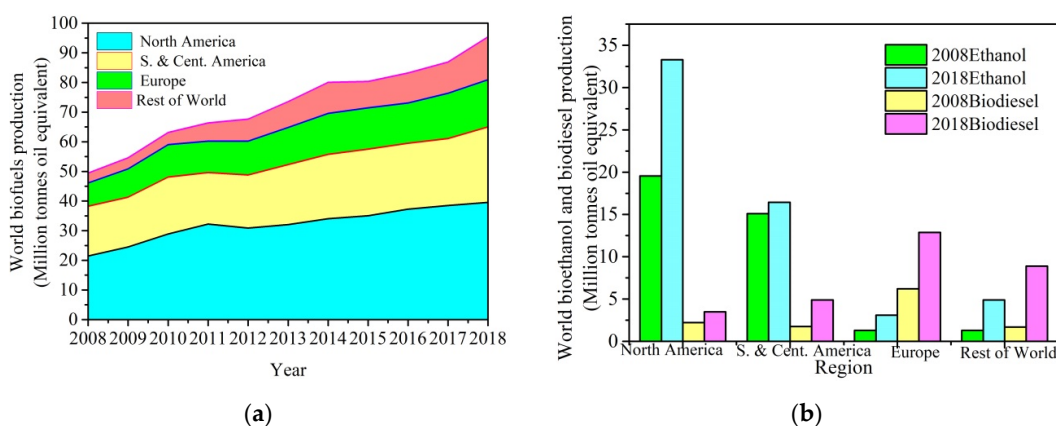
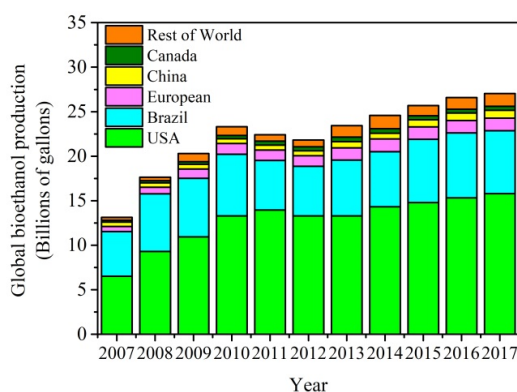


Figure 1. Cont.



(c)

Figure 1. The situation of global and regions biofuel production. (a) World biofuel production (adapted from BP 2019 [9]); (b) world bioethanol and biodiesel production (adapted from BP 2019 [9]); (c) global bioethanol production (source: www.afdc.energy.gov/data/).

Because bioenergy potential estimation is the first step to understanding bioenergy from the industrial chain and its development potential in the future, it is necessary to estimate biomass potential. So far, bioenergy estimation has been highlighted in the renewable energy field in order to establish a comprehensive understand of bioenergy development [29]. Biomass energy estimation methods include the statistical data method [32,33], estimation integrating remote sensing (RS), and geographic information system (GIS) techniques [34–36]. Owing to the ease in data acquisition, the statistical data method is the most commonly used method in biomass and bioenergy potential estimation at present [37]. The statistical data method of estimation involves subtracting the amount of resources used for other purposes and the amount of each possible type of biomass that can be used for bioenergy production, as well as the losses incurred in the process of collection, transportation, etc. The amount remaining is multiplied by the energy conversion coefficient and converted into a unit of energy [38,39]. As new methods, RS and GIS are mainly used to estimate biomass energy potential and obtain land area information for biomass cultivation. However, RS and GIS apply only to specific types of biomass because their theoretical basis is to measure the biomass of vegetation in the ecological domain and require a large workload, large scale, and suffer from lack of spatial information and other problems [40,41].

The total potential of using crop residues and waste crops to produce bioethanol was 491 GL per year, of which 73.9 Tg of dry waste crops can produce 49.1 GL bioethanol and about 1.5 Pg dry lignocellulosic biomass (442 GL bioethanol) every year [42]. Smeets et al. adopted a bottom-up solution to assess agricultural and forestry residues and potential wastes for a total 76–96 EJ yr^{−1} in the year 2050, and the bioenergy potential generated by surplus forest growth was 74 EJ yr^{−1} by 2050 [43]. Thrän et al. applied scenario approaches in three different global scenarios for 2010, 2015, 2020, and 2050. Their results showed a potential change in the development of “business as usual,” from 27 EJ in 2010 to 96 EJ in 2050. By contrast, the potential for “sustainable land use” schemes is much lower, with 18 EJ in 2010 and 16 EJ in 2050 [44]. In addition, there are also estimates of regional biomass energy potential. In extreme cases, De Wit et al. assumed the average yield of bioenergy crops and Europe’s bioenergy potential could be 5.1–9.3 EJ yr^{−1}. High-yielding lignocellulosic crops could double this potential [45]. Across Europe, the bioenergy potential of specialty bioenergy crops ranges from 1.7 to 12.8 EJ/y, with agricultural residues at 3.1–3.9 EJ/y and forestry residues at 1.4–5.4 EJ/y, respectively [46]. A total of 23.7 billion liters of second-generation ethanol could be produced from sugarcane residues, and 4.4 billion liters of Brazil’s corn and wheat residues extracted 600 million liters a year [23]. Furthermore, the potential of bioenergy in the Pacific Northwest states of the US [47], Albania [48], Switzerland [49], Poland [50], China [51], Malaysia [52], Japan [53], etc. were also more studied.

However, previous research has mainly focused on whole nations or a single zone. What is more, the biomass technology roadmap and bioenergy potential estimation of the Beijing-Tianjin-Hebei (B-T-H) region has not reported. In this paper, we successfully estimated three types biomass resources potential and bioenergy utilization potential based on a simple statistical data method and established the biomass energy technology roadmap of the B-T-H region. The rest of this paper is structured as follows: First, the description of technology roadmap and case information are presented in Section 2. Second, the energy potentials of specific types of bioenergy including crops straw, livestock and poultry waste, and municipal solid waste are estimated in Section 3. Third, the technology roadmap and bioenergy utilization potential of the B-T-H region and conclusion are discussed in Sections 4 and 5, respectively.

2. The Description of the Technology Roadmap and Case Information

2.1. The Description of the Technology Roadmap

Roadmaps can be developed for different levels of deployment, including global, national, and regional levels, as well as sector-specific or technology-specific roadmaps. A roadmap is a strategy or plan that describes the steps taken to achieve defined and agreed upon goals within a specified time frame. It defines the range of technical, policy, legal, financial, market, and organizational barriers to these goals and the known solutions to overcome them. The goal of the technology roadmaps is to accelerate the deployment of specific technologies or groups of technologies [27]. Existing roadmaps include the International Energy Agency (IEA) reported technology roadmap of bioenergy for transport in 2011 [54], the Technology Roadmap for Bioenergy Heat and Power in 2012 [55], and the Technology Roadmap for Delivering Sustainable Bioenergy in 2017 [27]. The technology roadmap for biomass energy, as depicted in Figure 2, maps the movement of energy from the supply of raw materials to the use of the final energy [56]. The technology roadmap is divided into the following four parts: biomass raw materials, biomass energy carrier forms, biomass energy demand forms, and energy end-use forms. The technology roadmap can provide solutions for regional biomass energy development and formulate energy development models according to the characteristics of different regions [27,46].

Biomass raw materials include crops (such as corn, wheat, sugarcane, soybean, rapeseed, etc.), forest waste, crop straw, human waste, animal waste, and municipal solid wastes [30] (see Figure 2). The basic function of the raw materials supply is to provide raw materials for the preparation of biomass energy. The supply of raw biomass material is the basis for the production of biomass energy. Raw material harvesting, material selection, storage and drying, and transport are the premise of energy technology transformation [57]. Different energy carriers are obtained from raw biomass material using certain transformation technologies. There are four forms of energy carriers—bioethanol, biodiesel, biogas, and densified solid. Corn, sugarcane, and wheat can be hydrolyzed by fermentation to produce bioethanol [58]. Lignocellulose is mainly used to prepare bioethanol through fermentation, gas synthesis, liquefaction, and refining [59]. Biodiesel oil is prepared by pyrolysis, transesterification, or catalytic hydrogenation from rapeseed, soybean, and other oil plants [60]. Biogas is generated from human waste, animal waste, and municipal solid waste through fermentation and pyrolysis gasification technology [61]. Densified solid fuel is processed by densification technology from crops straw and forest wastes [62–64].

Energy demand is related to the different energy carriers. The relationship between specific energy carriers and different forms of energy demand are shown in the Figure 2. The different forms of energy demand include fuel [65], heat [66], electricity [67], and refrigeration [68], depending on the application scenario. Different forms of energy terminal utilization have different forms of energy demand—for example, energy requirements for building energy come in the form of heating, electricity generation, and cooling [69–71].

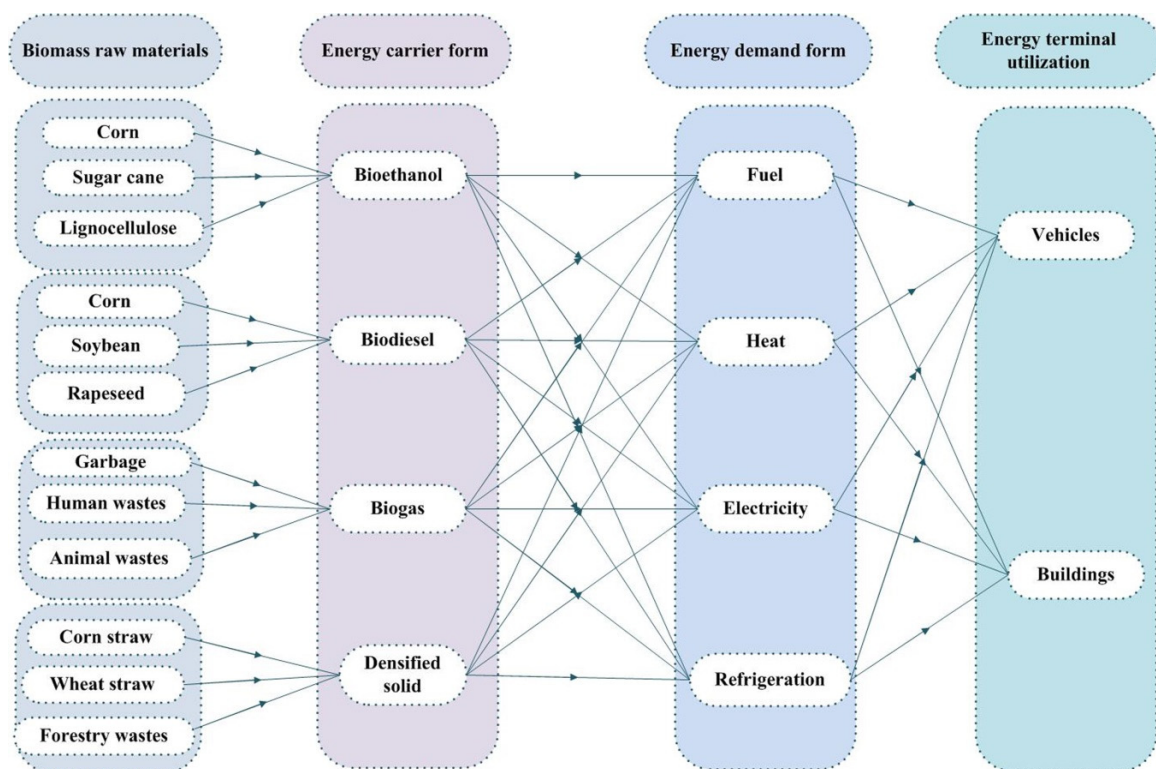


Figure 2. The technology roadmap of bioenergy: from biomass raw materials to final energy use [27].

2.2. The Description of Case Information

The B-T-H region is China's "capital economic circle." The GDP of the B-T-H region accounted for 9.54% of the country's total GDP. The per capita income in 2018 of Beijing, Tianjin, and Hebei residents was \$20,030 USD, \$17,244 USD, and \$6824 USD, respectively, which can be seen from Appendix A. While world biofuel production is increasing progressively year after year, China's biomass development is in its stage, and biomass development in the B-T-H region still requires significant progress. Biofuel production data in the Beijing-Tianjin-Hebei region are incomplete or even absent. Economic development promotes the development of biomass energy. Therefore, the biomass production of Beijing, Tianjin, and Hebei by analogy based on the same level of economic development in the world is shown in Appendix A.

The region covers an area of 216,000 square kilometers, accounting for 2.3% of China's total area, and has a population of 110 million, accounting for 7.2% of China's total. Due to rapid economic development, the environmental pollution in this area is serious, particularly in Hebei. Hebei Province has the highest density of coal consumption and heavily polluting industries in China [72]. Additionally, the B-T-H region has some of the most severe air pollution in China. In 2015, among the top 10 polluted cities in China, seven were located in the B-T-H region, and six cities were located in this region in 2016 [73,74].

The B-T-H region belongs to the northern plain, and its crop straw yield is very high, amounting to approximately 50 million tons per year. However, most of these resources are discarded or incinerated in the fields by local farmers, which leads to the waste of resources and seriously pollutes the environment. In response to the thorny issue of environmental pollution, the steel industry's ultra-low emissions and bulk coal replacement policies in the B-T-H region have improved the environmental situation, at least to some extent. Nevertheless, it is still necessary to control environmental pollution from the source. The biofuel process can turn waste straw, feces, and urban household waste into usable biomass energy and can take advantage of it in areas such as heating and power generation in the region. Based on

the above facts, estimating the region's bioenergy potential is therefore a top priority in developing a technology roadmap, which is particularly important in this article.

2.3. The Limitations of This Work

The B-T-H region has a limited variety of biomass resources, and not all biomass potential has been estimated. The types of biomass energy available are also limited, and the rice ratio, collection efficiency, and energy conversion efficiency are different from each other. The estimation method based on statistical data is theoretical, and we need to systematically map the process of biomass energy production from the collection of raw materials to the final energy utilization. The planning and utilization of the B-T-H region's biomass technology roadmap needs to be considered in many aspects, such as the support of national policies, the formulation of relevant laws, and the demand stability of the energy market, which all need to be studied over a long period of time.

3. The Potential Estimation of Bioenergy in the B-T-H Region

There are various kinds of biomass resources in the B-T-H region, including agricultural waste, livestock and poultry waste, and municipal solid waste. For those biomass resources, the amount of biomass resources and the potential for energy utilization are estimated by statistical data. All data are from the National Bureau of Statistics and are up-to-date.

3.1. The Estimation of Crops Straw Bioenergy Potential

3.1.1. Crop Residues

Generally speaking, crops residues are inedible plant parts left in the field after harvest. Some researchers also classify residues from crop packaging plants or residues discarded during crop processing as general crop residues [19]. The National Bureau of Statistics does not record special statistics on crops residues yield. There are also significant differences in the nature and rate of decomposition of crops residues. Rather than being directly measured, crops residues yield are estimated based on area and yield data for different crops and from research information on the straw/grain ratio [31,64–66]. Crops straw residues equation as follows:

$$M_i = \sum_1^n C_i r_i \beta \quad (1)$$

where M_i is the crops residues, C_i is the crops yield, r_i is the straw/grain ratio, n is the crop species, i is the number of crop species, and β is the collection coefficient. The straw/grain ratio of different crop species is shown in Table 1. The Appendix C is the straw/grain ratio range and collection coefficient.

Table 1. The straw/grain ratio of different crop species [19,23,42,75–77].

Crops	Straw/Grain Ratio
Rice	1.00
Wheat	1.28
Maize	1.10
Legumes	1.50
Potato	0.50
Peanut	1.01
Rapeseed	1.01
Cotton	3.62
Sugar beet	0.10
Tobacco	0.66

In order to estimate the potential of straw residues resources, classified crops yield, per land area amount of crops, and per capita amount of crops of the B-T-H region in 2017 are shown in Table 2. The crops including maize, wheat, potato, peanut, sugar beet, rice, cotton, rapeseed, legumes, and tobacco. According to the official statistics presented in Table 2, maize and wheat production were 20.35 million tons/year and 15.04 million tons/year in Hebei province, respectively. However, the two regions of Tianjin and Beijing produced 0.12 million tons/year and 0.03 million tons/year of maize and 0.06 million tons/year and 0.06 million tons/year of wheat. Apparently, Hebei produced far more wheat and corn than Tianjin and Beijing combined. The rest of the crop yields are very low compared to maize and wheat. The reason for this phenomenon is that, in Hebei, the area sown for grain crops large (Figure 3a), and the area sown to wheat and corn is much higher than that of other kinds of crops (Figure 3b).

Table 2. Classified crops yield (10^6 tons), per land area amount of crops (10^6 tons) and per capita amount of crops (kg) of the Beijing-Tianjin-Hebei (H-B-T) region in 2017 (source: <http://www.stats.gov.cn/>).

Crops	Category	Hebei	Tianjin	Beijing	Total
Rice	Production	0.50	0.26	0.00	0.76
	Per land area amount	0.03	0.23	0.00	0.26
	Per capita amount	6.71	14.97	0.03	21.71
Wheat	Production	15.04	0.62	0.06	15.72
	Per land area amount	0.80	0.55	0.04	1.39
	Per capita amount	200.02	35.47	2.85	238.34
Maize	Production	20.35	1.19	0.33	21.88
	Per land area amount	1.08	1.06	0.20	2.33
	Per capita amount	270.68	67.81	15.30	353.79
Legumes	Production	0.20	0.01	0.01	0.22
	Per land area amount	0.01	0.01	0.00	0.02
	Per capita amount	2.77	0.49	0.27	3.53
Potato	Production	13.40	0.15	0.0	1.36
	Per land area amount	0.07	0.01	0.00	0.08
	Per capita amount	17.81	0.85	0.28	18.94
Peanut	Production	1.03	0.01	N/A ¹	1.04
	Per land area amount	0.06	0.01	0.00	0.07
	Per capita amount	13.75	0.30	0.19	14.24
Rapeseed	Production	0.00	N/A ¹	N/A ¹	0.00
	Per land area amount	0.00	N/A ¹	N/A ¹	0.00
	Per capita amount	0.55	N/A ¹	N/A ¹	0.55
Cotton	Production	0.02	0.02	N/A ¹	0.04
	Per land area amount	0.01	0.02	N/A ¹	0.03
	Per capita amount	3.19	1.42	N/A ¹	4.61
Sugar beet	Production	0.06	N/A ¹	N/A ¹	0.06
	Per land area amount	0.03	N/A ¹	N/A ¹	0.03
	Per capita amount	8.30	N/A ¹	N/A ¹	8.30
Tobacco	Production	0.00	N/A ¹	N/A ¹	0.00
	Per land area amount	0.00	N/A ¹	N/A ¹	0.00
	Per capita amount	0.00	N/A ¹	N/A ¹	0.03

¹ Means none available, because of no statistics for crop production according to National Bureau of Statistics.

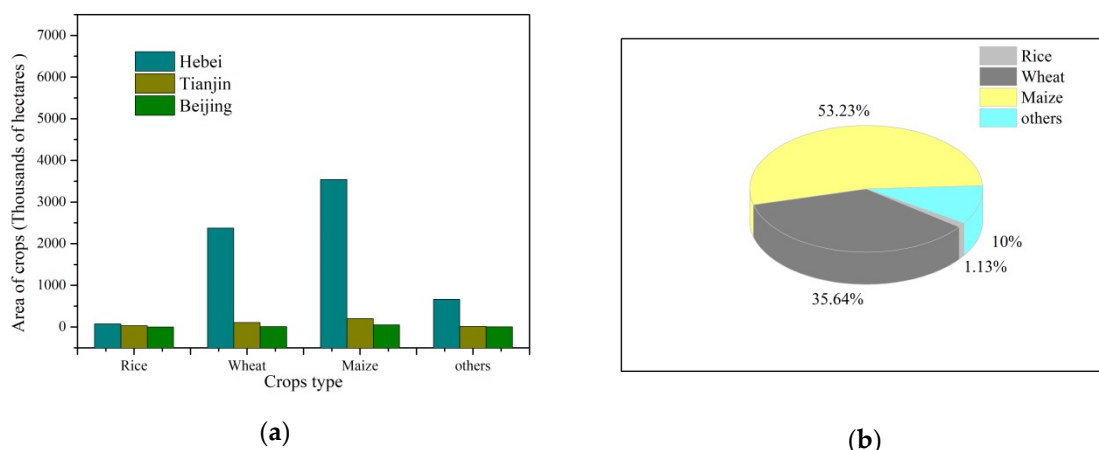


Figure 3. The cultivated area of crops in the B-T-H region in 2017. (a) The cultivated area of maize, wheat, rice, and crops total in Hebei, Tianjin, and Beijing, respectively. (b) The cultivated area of maize, wheat, rice, and crops total in Hebei (source: <http://www.stats.gov.cn/>).

As a renewable resource, a large quantity of residue is produced annually by a wide range of crops grown in the B-T-H region. Crops residues of B-T-H region in 2017 are shown in Table 3. The estimated maize residues in the B-T-H region are 18.05 million tons, which is the highest amount of crop residue. Currently, estimated residues from Hebei constitute 93% of total residues from the region. Maize is the most widely grown crop in Hebei. Wheat residue production is about 15.098 million tons in 2017 in the B-T-H region; thus, maize and wheat together account for 91% of total crop residues in the B-T-H region. After corn, wheat is the second most widely used starchy crop for food or feed in the B-T-H region. Due to the lack of effective utilization in the B-T-H region, a large amount of concentrated agricultural waste (e.g., corn cobs) is produced every year, causing environmental pollution. In the B-T-H region, crops residue is mainly used as food or feed, and this produces about 36.69 million tons of straw, stem, and leaf residues, which can be used in fermentation processes, considering that 50% of these residues are simply left in the field [19]. According to one calculation method [23], 3.49 billion liters of cellulosic ethanol could be produced from this surplus biomass. In addition, these residues can be made into solid fuel via densification technology. Song et al. studied the densified solid fuel of corn residues in district heating systems for rural and urban heating in winter [67]. The economic value of collected crop residues is shown in Appendix B.1.

Table 3. Crops residues in 2017 (10^6 tons).

Crops	Hebei	Tianjin	Beijing	Total
Rice	0.38	0.20	0.00	0.58
Wheat	14.44	0.60	0.06	15.10
Maize	16.79	0.98	0.27	18.05
Legumes	0.23	0.01	0.01	0.25
Potato	0.50	0.01	0.00	0.51
Peanut	1.16	0.01	0.00	1.17
Rapeseed	0.09	N/A ¹	N/A ¹	0.09
Cotton	0.65	0.07	N/A ¹	0.72
Sugar beet	0.05	N/A ¹	N/A ¹	0.05
Tobacco	0.00	N/A ¹	N/A ¹	0.00
Total	34.30	1.87	0.35	36.52

¹ Means none available, because of no statistics for crop production according to the National Bureau of Statistics.

3.1.2. The Energy Potential Estimation of Crops Residues

Biomass energy is converted into the energy demand form used by consumers. It is necessary to convert crop residues into available forms of heat, electricity, or solid fuels. The solid fuels for home heating or cooking can replace coal. In the B-T-H region, families install modified coal gas plants in order to use natural gas for heating or cooking, so it is very important to estimate the energy end-use value.

Formula for calculating energy potential of crop straw is as follows [75]:

$$Q_i = \sum_{1}^n M_i k_i \quad (2)$$

where Q_i is the energy potential of the crop straw and k_i is the low value of the crop coal coefficient.

The heating value of crop residues is about 3×10^6 kcal/Mg (1 Tg = million Mg), which is about 50% of that of coal and 33% of that of diesel [76]. The value of crop residue energy varies with different kinds of crops. For example, the energy value of rice is 3015 kcal/kg, and that of hay is 3738 kcal/kg [78]. Besides, the crop residue fuel value is 18.6×10^9 J, two barrels (bbl) of diesel, 3×10^6 kcal, or 16×10^6 BTU [79]. In this paper, the same coefficient of folded coal is applied to the estimation of crop residue energy. Table 4 presents the coal equivalents for crops residues in the B-T-H region for the year 2017. According to these estimates, straw resources in the region have a potential of about 36.52 million tons of coal equivalent (Table 3). As corn and wheat straw resources are the largest, their crop residue coal equivalents are also highest, at 9.02 million tons and 7.5 million tons, respectively. Hebei has the highest share of crop residue coal equivalence, with a value of about 17.15 million tons, which is equal to 0.1×10^{15} kcal of total energy of crops residues in this area and accounts for 93% of the B-T-H region. Tianjin's and Beijing's share of the straw are far less than the potential resources of Hebei, with coal equivalent values 0.93 and 0.17 million tons, respectively, which are equal to 0.5×10^{13} kcal and 0.75×10^{12} kcal (Figure 4). Obviously, the crops residues potential of the B-T-H region is enormous. Hebei is the region with the greatest potential for the use of crop residues in energy generation. Therefore, according to the characteristics of the B-T-H region, in terms of crop residue biomass resources, there is a huge market for energy development in Hebei.

Table 4. Crop residue coal equivalent calculations in 2017 (10^6 tons).

Crops	Hebei	Tianjin	Beijing	Total
Rice	0.19	0.10	0.00	0.29
Wheat	7.22	0.30	0.03	7.55
Maize	8.40	0.49	0.14	9.03
Legumes	0.12	0.00	0.00	0.13
Potato	0.25	0.00	0.00	0.26
Peanut	0.58	0.00	0.00	0.59
Rapeseed	0.05	N/A ¹	N/A ¹	0.05
Cotton	0.33	0.03	N/A ¹	0.36
Sugar beet	0.02	N/A ¹	N/A ¹	0.02
Tobacco	0.00	N/A ¹	N/A ¹	0.00
Total	17.15	0.93	0.17	18.26

¹ Means none available, because of no statistics for crop production according to the National Bureau of Statistics.

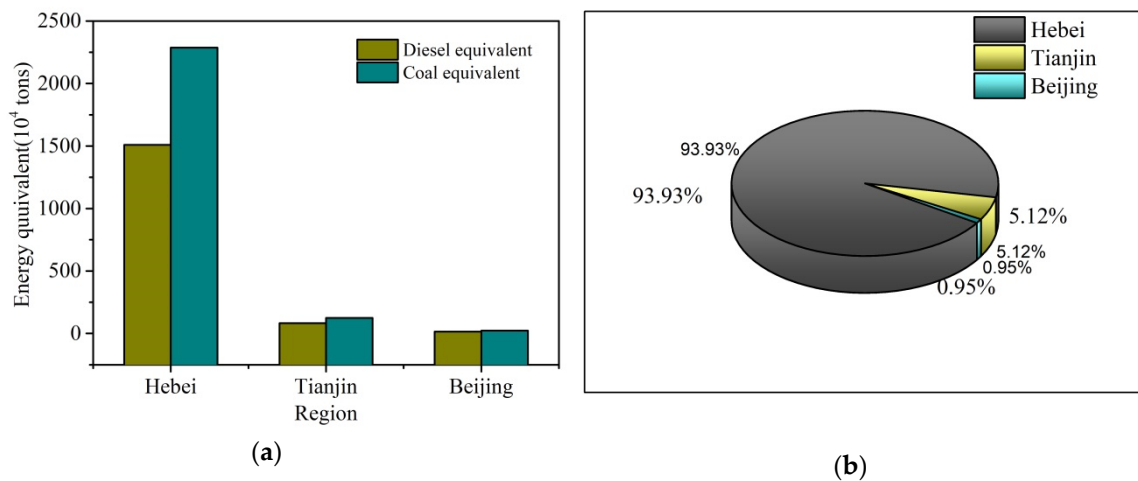


Figure 4. The energy value in the B-T-H region in 2017. (a) The curve of diesel equivalent and coal equivalent in Hebei, Tianjin, and Beijing, respectively. (b) The energy value proportion of Hebei, Tianjin, and Beijing, respectively.

3.2. The Estimation of Human, Poultry, and Livestock Manure Bioenergy Potential

3.2.1. The Estimation of Human, Poultry, and Livestock Manure Production

Livestock and poultry manure are important biomass resources and are the main raw materials of biogas fermentation. The development of livestock and poultry breeding has produced a large amount of feces. If it is not treated, directly piled up, or discharged at will, serious ecological and environmental problems will result, which will pollute water and air and waste organic nutrient resources. From the perspective of circular agriculture and economy, livestock and poultry are ideal sources of biogas raw materials. The biogas project organically combines pollution control of livestock and poultry waste with energy recycling, thus promoting the healthy development of the livestock and poultry breeding industry and alleviating energy shortage problems.

This section is mainly based on the livestock and poultry species, livestock and poultry output, and end-of-year data provided by the National Bureau of Statistics, which is combined with the excretion coefficient, feeding cycle, COD emissions, and methane production coefficient to estimate the physical volume [80,81], methane production volume, and energy potential of livestock and poultry feces resources in the B-T-H region in 2016. COD is the general term for the amount of organic matter in feces.

Livestock and poultry excrement and COD yield are calculated as follows [75]:

$$M_j = \xi \sum_{i=1}^n (N_i T_i \eta_{ja} + N_j T_j \eta_{jb}) \quad (3)$$

Where M_j is poultry and livestock manure production, ξ is collection coefficient of 60%, N_j is breeding quantity, T_j is feeding cycle, η_{ja} is fecal coefficient, η_{jb} is urinary fecal coefficient, j is livestock and poultry species, and $j = 1, 2, 3 \dots n$.

The feeding cycle for pigs is 199 days; the feeding cycle for cattle, sheep, horses, donkeys, and poultry is more than one year, and 365 days is the feeding cycle. Table 5 shows the excretion coefficient, COD production coefficient, and feeding cycle [75,77,80,81].

Table 5. Excretion coefficient, COD production coefficient, and feeding cycle in 2016 [75,77,80,81].

Species	Excretion Coefficient (kg/day)	COD Production Coefficient (kg/day)	Feeding Cycle (day)
Pig	3.39	0.36	199
Sheep	2.60	0.01	365
Cattle	30.40	4.09	365
Poultry	0.37	0.025	365
Horse	15	N/A ¹	365
Donkey	13	N/A ¹	365
Mule	13	N/A ¹	365
Human	0.08	0.075	365

¹ Means none available.

Livestock waste can be used in three ways—as fertilizer, feed, and energy. To estimate the energy potential of human, animal, and poultry wastes, the number of humans, animals, and poultry must be found. Fecal-based feeds are currently not recommended due to potential safety concerns. In the anaerobic fermentation process, the manure can produce methane and provide organic matter, so it is recommended that the manure be converted into energy fertilizer in order to extract biogas from the slurry [67]. The quantity of humans, livestock, and poultry is shown in Table 6. The B-T-H region is home to large populations of humans, livestock, and poultry.

Table 6. The quantity of humans, livestock, and poultry in 2016 (10⁶) (source: <http://www.stats.gov.cn/>).

Species	Situation	Hebei	Tianjin	Beijing
Pig	Marketable stock	34.34	3.75	2.75
	Standing stock	19.58	1.80	1.65
Sheep	Marketable stock	23.04	0.69	0.70
	Standing stock	12.28	0.43	0.60
Cattle	Marketable stock	3.32	0.20	0.07
	Standing stock	3.60	0.26	0.16
Poultry	Marketable stock	607.72	79.11	38.83
Horse	Standing stock	0.06	0.00	0.00
Donkey	Standing stock	0.17	0.01	0.00
Mule	Standing stock	0.05	0.00	0.00
Human	Year-end residents	74.70	15.62	21.73

According to Table 7, the total excrement production in the B-T-H region is about 159.63 million tons, including human feces, of which the total livestock and poultry excrement production in Hebei region is 139.35 million tons, 12.05 million tons in Tianjin, and 7.63 million tons in Beijing, respectively. The total livestock and poultry excrement production in Hebei accounts for 87.21% of the whole B-T-H region. Therefore, the excrement in the B-T-H region mainly comes from Hebei. In terms of livestock and poultry species, poultry feces in the B-T-H region ranked first, accounting for 35.33% of the total, followed by cow feces (accounting for 33.03%), pig feces (accounting for 15.65%), and sheep feces (accounting for 14.29%). The excrement of horses, donkeys, mules, and humans is very small, and the excrement of these three kinds of livestock are 0.02 million tons total. It can be seen that cattle, poultry, pigs, and sheep are the main sources of feces in the B-T-H region. The proportion of human, animal, and poultry excrement in Tianjin and Beijing is basically the same as that in Hebei.

COD is the general term for the content of organic matter in feces, and methane is mainly produced by COD. Therefore, it is very necessary to calculate the amount of COD in feces in order to calculate the potential methane produced from feces. Table 8 shows the amount of COD produced by livestock and poultry feces in the B-T-H region. As can be seen from Table 8, the main human, livestock, and poultry COD production in the B-T-H region is 15.46 million tons, of which Hebei accounts for 85.02% of the total, Tianjin accounts for 8.68%, and Beijing accounts for 6.29% (Figure 5). The amount of COD

produced by cattle accounts for 44.06% of the total, the amount of COD produced by poultry accounts for 25.69% of the total, the amount of COD produced by pigs accounts for 6.91% of the total, and the amount of COD produced by sheep is very small (accounting for approximately 0.53%).

Table 7. The estimation of human, livestock, and poultry waste production (10^6 tons).

Species	Situation	Hebei	Tianjin	Beijing	Total
Pig	Marketable stock	13.90	1.52	1.11	16.53
	Standing stock	7.92	0.73	0.67	9.32
Sheep	Marketable stock	13.12	0.39	0.40	13.91
	Standing stock	6.99	0.25	0.34	7.58
Cattle	Marketable stock	22.10	1.34	0.49	23.93
	Standing stock	23.93	1.72	1.08	26.73
Poultry	Marketable stock	49.24	6.41	3.15	58.80
Horse	Standing stock	0.19	0.00	0.01	0.20
Donkey	Standing stock	0.49	0.02	0.01	0.52
Mule	Standing stock	0.15	0.00	0.00	0.15
Human	Year-end resident	1.31	0.27	0.38	1.96
Total		139.35	12.65	7.63	159.63

Table 8. The estimated COD production of human, livestock, and poultry waste (10^6 tons).

Species	Situation	Hebei	Tianjin	Beijing	Total
Pig	Marketable stock	1.48	0.16	0.12	1.76
	Standing stock	0.84	0.08	0.07	0.99
Sheep	Marketable stock	0.05	0.00	0.00	0.05
	Standing stock	0.03	0.00	0.00	0.03
Cattle	Marketable stock	2.97	0.18	0.07	3.22
	Standing stock	3.22	0.23	0.14	3.60
Poultry	Marketable stock	3.33	0.43	0.21	3.97
Human	Year-end resident	1.23	0.26	0.36	1.84
Total		13.14	1.34	0.97	15.46

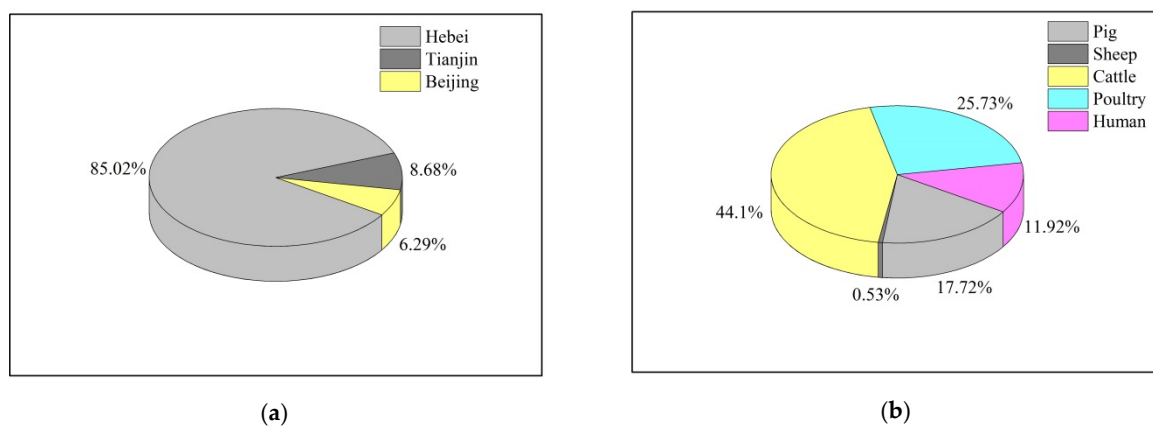


Figure 5. The COD value in the B-T-H region. (a) A pie chart of COD production in Hebei, Tianjin, and Beijing, respectively. (b) The COD value proportion of pigs, sheep, cattle, poultry, and humans, respectively.

3.2.2. The Energy Potential Estimation of Human, Livestock, and Poultry Waste

The energy potential of livestock and poultry manure is estimated by the amount of biogas produced by COD in feces. The biogas potential formula from manure is as follows [75]:

$$W_j = \sum_1^n M_{COD} g \beta \quad (4)$$

where W_j is the biogas potential from manure, M_{COD} is the COD yield, g is COD removal rate, value of 85%, β is the methane coefficient produced by COD, which is 0.538 m³/kg.

Table 9 shows the potential of the B-T-H region to produce biogas, which is estimated to be 7.07 billion m³. The livestock and human manure capacity for Hebei province is 6.01 billion m³, accounting for 85.55% of the total. The poultry and animal feces biogas production quantity of Tianjin was 0.61 billion m³, accounting for 8.66% of the total. For Beijing, the poultry and animal feces biogas production quantity is 0.44 billion m³, accounting for 6.28% of the total. The coal equivalent of feces waste for the B-T-H region is shown in Table 10. The coal equivalent energy potential of human, livestock, and poultry wastes is 5.18 million tons. According to Tables 9 and 10, the potentials of total livestock and human manure in the B-T-H region are significantly different between regions, which may be ascribed to the level of economic development, population base, and topography. The economic evaluation is shown in Appendix B.2.

Table 9. The estimation of feces waste for biogas production (10⁸ m³).

Species	Situation	Hebei	Tianjin	Beijing	Total
Pig	Marketable stock	6.75	0.74	0.54	8.03
	Standing stock	3.85	0.35	0.32	4.52
Sheep	Marketable stock	0.23	0.01	0.01	0.25
	Standing stock	0.12	0.01	0.01	0.13
Cattle	Marketable stock	13.60	0.82	0.30	14.72
	Standing stock	14.72	1.06	0.66	16.45
Poultry	Marketable stock	15.22	1.98	0.97	18.17
Human	Year-end resident	5.61	1.18	1.63	8.42
Total		60.10	6.14	4.45	70.68

Table 10. The coal equivalent of feces waste (10⁶ tons).

Species	Situation	Hebei	Tianjin	Beijing	Total
Pig	Marketable stock	0.49	0.05	0.04	0.59
	Standing stock	0.28	0.03	0.02	0.33
Sheep	Marketable stock	0.02	0.00	0.00	0.02
	Standing stock	0.01	0.00	0.00	0.01
Cattle	Marketable stock	1.00	0.06	0.02	1.08
	Standing stock	1.08	0.08	0.05	1.21
Poultry	Marketable stock	1.12	0.15	0.07	1.33
Human	Year-end resident	0.41	0.09	0.12	0.62
Total		4.41	0.45	0.33	5.18

3.3. The Estimation of Municipal Solid Waste (MSW) Bioenergy Potential

3.3.1. The Production of MSW

Municipal solid waste (MSW) refers to materials disposed of in urban areas, including domestic waste and commercial waste, which are collected and disposed of by municipal authorities [82].

The three main MSW disposal methods are landfill, incineration, and composting [83]. The dominant form of wastes disposal in China is landfill, handling over 80% of the treated MSW [84]. Methane is produced as a byproduct of the anaerobic decomposition of MSW in landfill [85]. According to statistics, the per capita daily garbage production volume of large cities is up to 1.4 kg and about 1 kg in small and medium-sized cities [77].

The astonishing amount of municipal solid wastes produced per year is presented in Table 11. The municipal solid waste clearance is 9.24 million tons in Beijing, 6.99 million tons in Hebei province, and 3.06 million tons in Tianjin, respectively, which amounts to a total of 19.31 million tons in the B-T-H region. Harmless garbage treatment no longer pollutes the environment and can be used. The rate of harmless garbage treatment has reached more than 99%, according to the National Bureau of Statistics. According to Table 11, harmless waste disposal amounted to 9.23 million tons in Beijing, including 4.38 million tons of sanitary landfill waste and 3.26 million tons of burning waste, which is the largest amount in the B-T-H region.

Table 11. Municipal solid waste (MSW) production in 2017 (source: <http://www.stats.gov.cn/>).

Category	Beijing	Hebei	Tianjin	Total
Wastes clearance volume (10^6 tons)	9.24	7.00	3.07	1.93
Harmless disposal volume (10^6 tons)	9.24	7.00	2.90	1.93
Sanitary landfill wastes (10^6 tons)	4.38	3.91	1.52	38.62
Burning wastes	326.50	284.80	137.6	7724.84
Harmless treatment rate	99.00%	99.80%	99.40%	None

3.3.2. The Energy Potential Estimation of MSW

The calculation formula for methane production from municipal solid waste landfill treatment is as follows [65]:

$$M_{CH_4} = (M_T \times M_F \times L_O - R) \times (1 - OX) \quad (5)$$

where M_{CH_4} is the methane yield of domestic garbage (10^4 tons), M_T is the volume of urban domestic garbage collection (10^4 tons), and M_F is the sanitary landfill treatment rate of urban domestic garbage. L_O is methane production potential per ton of garbage in each management plant, and R is methane recovery volume of 0, OX is oxidation factor of 0.1.

$$L_O = (MFC \times DOC \times DOC_F \times F \times 16/12) \quad (6)$$

where MFC is the methane correction factor of each management plant landfill, and the MFC of a well-managed landfill is 1, DOC refers to biodegradable organic carbon (kg carbon/kg waste) in domestic waste (with a value of 9.0%), DOC_F is the decomposable DOC ratio in household garbage (whose value is 0.5), F is methane volume ratio of 0.5, and $16/12$ refers to the molecular weight ratio of methane to carbon [75].

The energy potential of methane from municipal solid wastes landfill is calculated as follows:

$$E = M_{CH_4} \times d \times k \quad (7)$$

where E is the energy potential of methane production from urban domestic waste (10^4 tons standard coal), M_{CH_4} is the methane production volume of urban domestic waste, d is the density of methane of 0.69 kg/m^3 , k is the conversion coal coefficient of methane, the low calorific value of methane is $35,822 \text{ KJ/m}^3$, and the conversion coal coefficient is 1.78 [75].

The energy potential estimation of MSW is shown in Table 12. In terms of total amount, the total amount of methane treated by urban household waste in the B-T-H region is 0.27 million tons (384 million m^3), equivalent to 0.47 million tons of standard coal. From a regional perspective, Beijing has the highest methane production from urban household waste, with an output of 0.12 tons, followed by Hebei with 0.11 million tons, and Tianjin with 0.04 million tons.

Table 12. The biogas production and coal equivalent of MSW.

Category	Beijing	Hebei	Tianjin	Total
Methane production from landfill treatment (10^6 tons)	0.12	0.11	0.41	0.27
Methane coal equivalent produced by landfill treatment (10^6 tons)	0.21	0.19	0.73	0.47
Methane produced by landfill treatment (hundred million m^3)	1.71	1.53	0.60	3.84

4. The Technology Roadmap of the B-T-H Region

By estimating the available potential of B-T-H region, the distribution of crops residues; human, poultry, and livestock manure; and MSW are illustrated in Figure 6a–c, respectively. In terms of crop residues, Hebei has abundant biomass resources, of which the crop residue coal equivalent is more than 18 million tons (Figure 6a). It can be concluded from Figure 6b that MSW resources are mainly distributed in Beijing. According to Figure 6c, the human, poultry, and livestock manure resources are mainly concentrated in Hebei. As a result, economically underdeveloped areas are rich in crop residues and livestock and poultry excrement resources, and economically developed cities are rich in urban household garbage.

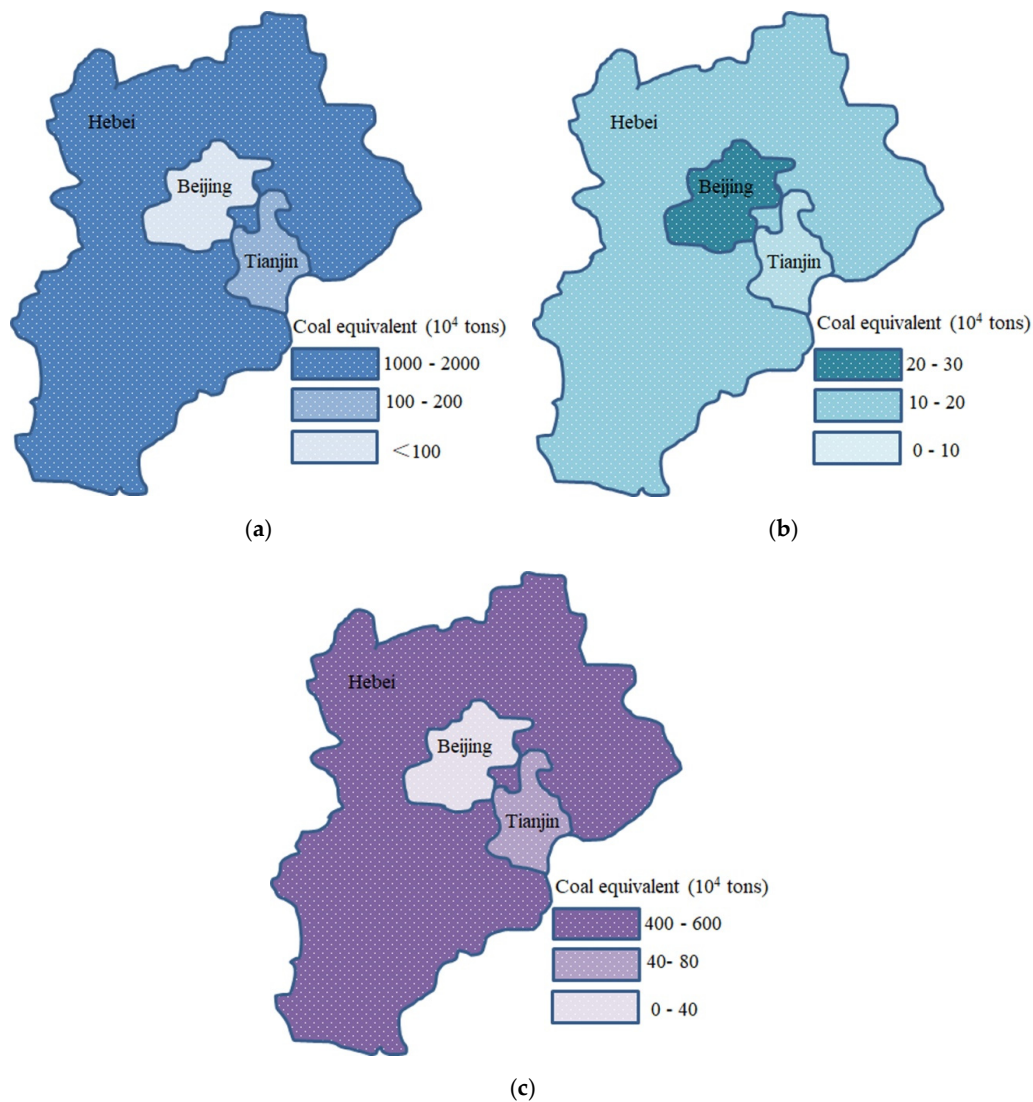


Figure 6. Biomass energy potential in the B-T-H region. (a) The distribution of crops residues energy potential in the B-T-H region. (b) The distribution of MSW energy potential in the B-T-H region. (c) The distribution of human, poultry, and livestock manure energy potential in the B-T-H region.

On the basis of abundant biomass resources in the B-T-H region, the suitable technology roadmap of biomass energy development in the B-T-H region from a resource perspective is shown in Figure 7, where the light orange items represent the technology roadmap for the B-T-H region. The biogas roadmap presents the movement from garbage, human waste, and animal waste to building energy demand, which is suitable for the development of the B-T-H region's urban household garbage and livestock manure biomass resources. The densified solid roadmap presents the movement from the corn straw, wheat straw, and forestry wastes to building energy demands. Forest resources in B-T-H region are limited, so this paper does not address their use.

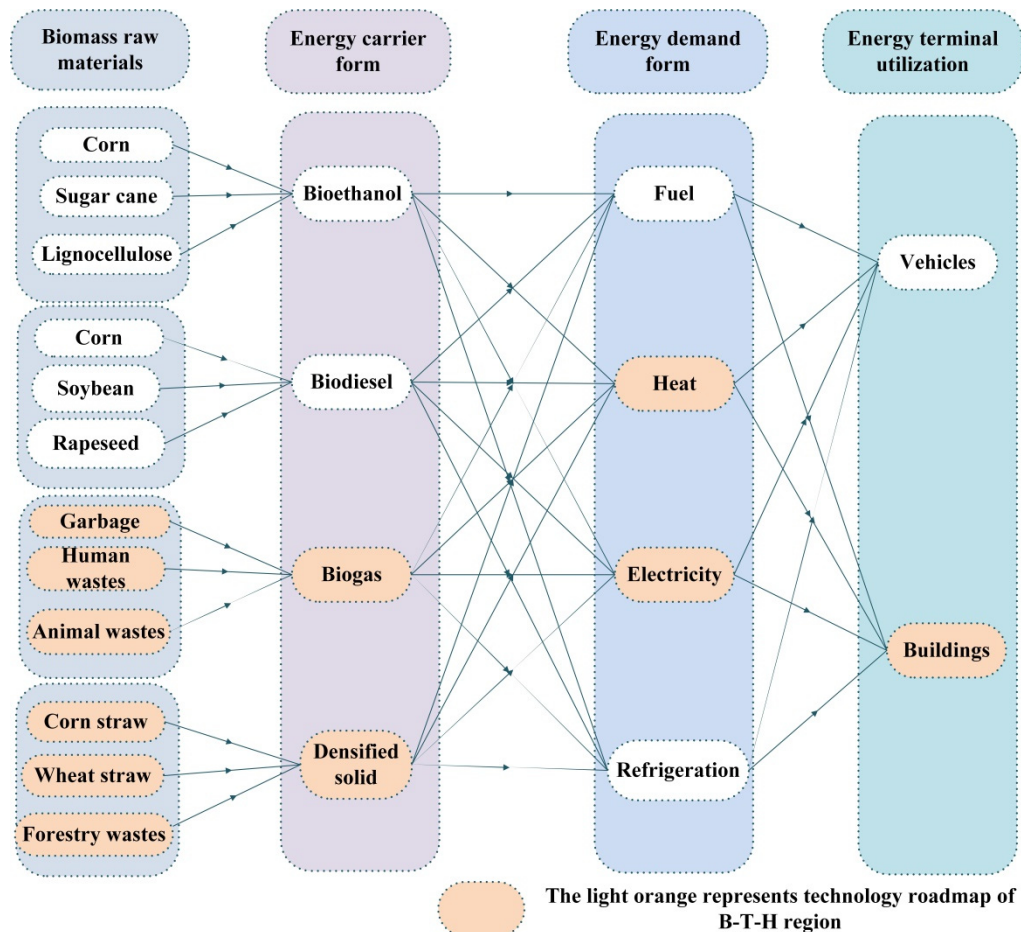


Figure 7. The suitable technology roadmap of biomass energy development in the B-T-H region.

When biomass raw materials are collected, processed, and converted into usable energy forms, energy waste and incomplete conversion are inevitable. Due to technical problems, conversion efficiency is crucial to the full utilization of energy. Of course, in the process of using energy, the loss of equipment will waste a certain percentage of energy. Therefore, the energy conversion parameters from raw materials collection to energy utilization is shown in Table 13. Figure 8 gives the energy grid in each progress according to references [67,75–77]. Urban household garbage and livestock waste resources are used by advanced gasification and fermentation technologies, which can obtain 7.45 billion m³ of biogas. Furthermore, biogas is used to generate electricity and heat. Based on the excrement conversion efficiency of 75.83% and utilization efficiency of 55% [65], biogas in the B-T-H region can generate 79.45 billion KJ heat (Figure 8).

Table 13. Energy conversion parameter [75–77].

Biomass Raw Materials	Collection Coefficient	Energy Carrier Form	Energy Loss in Infrastructure	Machining Efficiency	Energy Demand form	Energy Conversion Efficiency	Caloric Value (KJ/Kg)	Energy Utilization Efficiency
Crops	75%	Biogas	5%	0.30 m ³ /kg	Heating	75.83%	12,572.70	55%
					Power (central)	N/A ³	N/A ¹	
		Densification	5%	92%	Heating	75.83%	12572.70	45%
					Power (central)	0.56KW h/Kg	N/A ¹	
MSW	90%	Biogas	N/A ¹	N/A ¹	Heating	75.83%	25.58	55%
					Power (central)	1.25 KW h/m ³	N/A ¹	55%
Excrement	60%	Biogas	15%	0.54 m ³ /kg	Heating	75.83%	25.58	55%
					Power (central)	1.25 KW h/m ³	N/A ¹	55%

¹ Means none available.

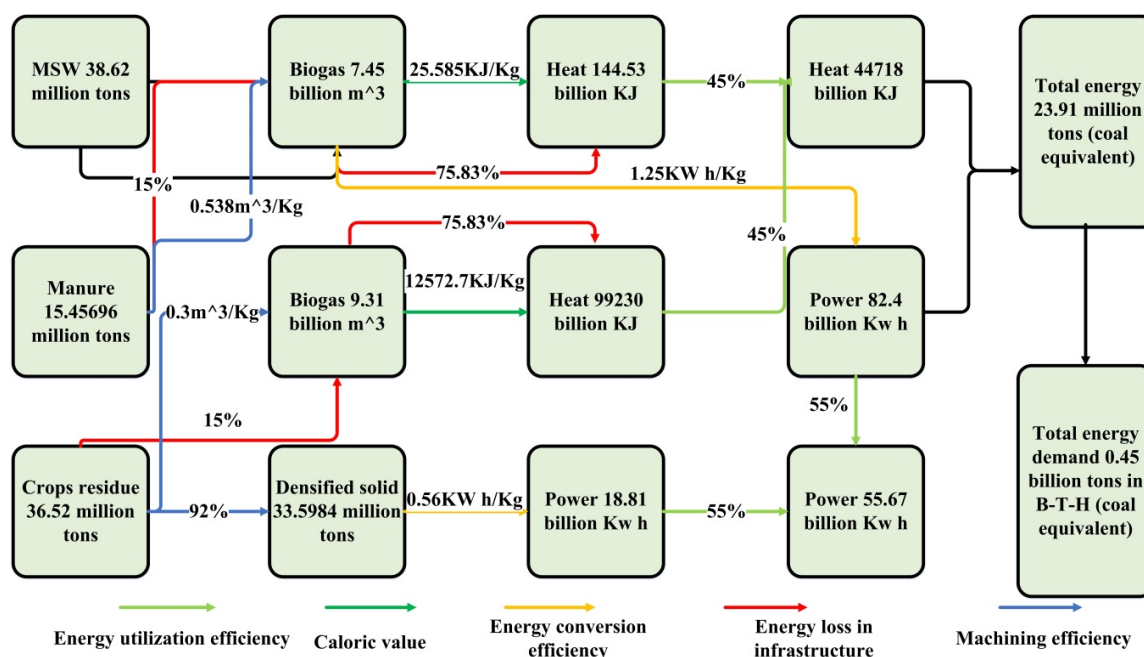


Figure 8. The energy grid of three biomass energy with energy demand total in the B-T-H region [67,75–77].

Although methane power generation technology is not as mature as methane heating technology, the application of biogas in power generation can still be used as the roadmap for biomass energy technology in the B-T-H region. The goal of the technology roadmap is to accelerate the deployment of specific technologies or groups of technologies; therefore, it is also a challenge for the biomass energy technology to make a good use of urban household garbage and livestock and poultry excrement for power generation in the B-T-H region. If the biogas power generation conversion efficiency is the same as that of crop straw (1.25 KW h/m³ and utilization efficiency of 45% [77]), then 9.30 billion KW h of electric energy will be produced (Figure 8). Buildings such as shopping malls, homes, and office buildings need to consume a lot of electric energy every day and a lot of thermal energy in the winter. Therefore, the electric energy and thermal energy generated by livestock and poultry excrement and urban household garbage in the B-T-H region can be used for the heat and power consumption of buildings. Among various biomass uses, densification technology is a typical means of the crop residue conversion. Crops residues are produced, harvested, collected, pretreated, stored, and converted into solid particles. Assuming that the compressing and shaping technology conversion efficiency is 92% and the utilization efficiency is 55% with a calorific value of 12,572.70 KJ/Kg [77], then 54,576 billion KJ will be generated. If the crop residue power generation conversion efficiency is the same as that of forest biomass (0.56 kW h/Kg [77]), it would product 12.654 billion kW h, which can be used in buildings (Figure 8).

According to references [86–88], the total energy demand of B-T-H is 455.29 million tons of coal equivalent, which is shown in Table 14. Among them, the percentage of total energy demand for coal, petroleum, and natural gas in Hebei are 87.31%, 7.97%, and 4.23% respectively. We found that the total residential demand of Tianjin and Beijing are 11.02 and 16.97 million tons coal equivalent. So, a final calculation on how much percent of the total energy demand can be obtained from biomass is completed. The total 29.31 million tons of coal equivalent calculated from biomass wastes can account for 5.30% of the total energy demand of B-T-H and exceeds 5% of the total residential demand in Tianjin and Beijing. Therefore, only 5.30% of the total energy demand can be provided from biomass wastes for the B-T-H region's total energy demand, but it can address the energy needs of some residents in Beijing and Tianjin. Therefore, it is very necessary and wise to pursue this technology roadmap.

Table 14. Energy demand of the B-T-H region in 2017 [86–88].

Energy	Hebei	Tianjin	Beijing
Total energy demand (10 ⁶ tons coal equivalent)	303.85	80.11	71.32
Coal percentage of total energy demand (%)	83.71	48.00	5.65
Petroleum percentage of total energy demand (%)	7.97	N/A ¹	33.8
Natural gas percentage of total energy demand (%)	4.23	1.02	31.8
Total residential demand (10 ⁶ tons coal equivalent)	N/A ¹	11.02	16.97
Residential demand Heat (10 ⁶ million KJ)	N/A ¹	102.18	N/A ¹
Electricity (10 ² million KW h)	N/A ¹	99.68	N/A ¹

¹ Means none available.

5. Conclusions

This paper conducted research into the estimation of the B-T-H region's biomass energy potential from crop residue, livestock and poultry manure, and municipal solid wastes by the statistical data estimation method. According to the characteristics of the three types of energy potential in the B-T-H region, the corresponding technology roadmaps have been formulated. The available energy of biomass is obtained by a comprehensive consideration of energy utilization and energy efficiency.

The following conclusions may be drawn:

1. Through statistical data analysis, the total available biomass resource is 90.60 million tons, of which 36.52 million tons come from crop residue, 15.46 million tons from manure, and 38.62 million tons from MSW. The crops residue potential of Heibei region is enormous, accounting for 93% of the B-T-H region total, which is equal to 0.10×10^{15} kcal of total energy of crops residues in this area. Therefore, a huge energy development market in Hebei may exist.
2. The potentials of crops residue and livestock and human manure in the different components of the B-T-H region have significant regional difference, which may be ascribed to the level of economic development, population base, and topography. From a resource perspective, the suitable technology roadmaps are the biogas development roadmap and the densified solid development roadmap.
3. Taking into conversion efficiency and energy use efficiency account, an estimate of the final energy use of available biomass energy is obtained. The total available bioenergy of heat is 44,718 billion KJ, the total available bioenergy of power is 55.67 billion KW h and the total available bioenergy of coal equivalent is 23.91 million tons.

In conclusion, it is important for the B-T-H region to develop technology roadmaps. Further policy, legal, financial, and market research in the B-T-H region is necessary to develop accurate technology roadmaps for the region.

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Appendix A

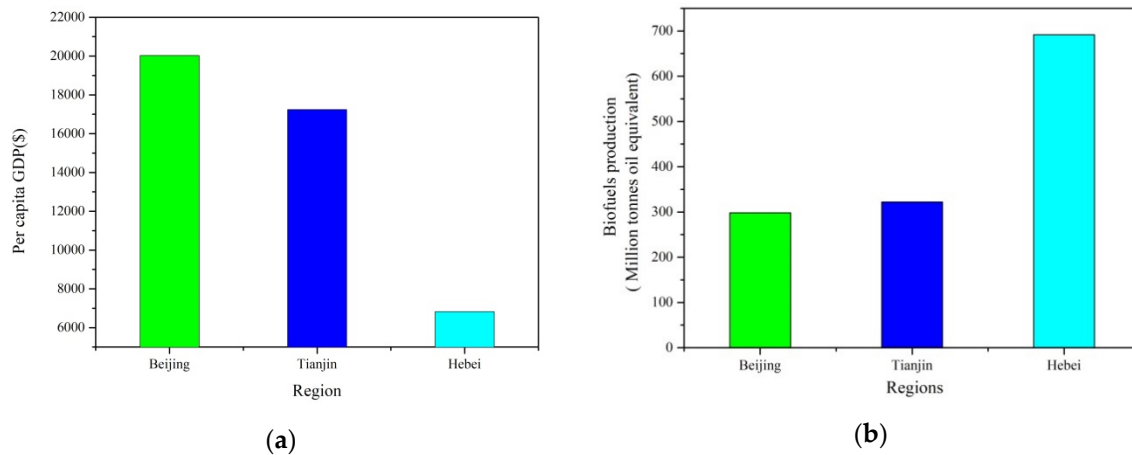


Figure A1. Biofuel production and per capita GDP of the Beijing, Tianjin, and Hebei regions. (a) The per capita GDP of the Beijing, Tianjin, and Hebei regions (source: <https://data.worldbank.org.cn/>); (b) Biofuel production of the Beijing, Tianjin, and Hebei regions by analogy based on the same level of economic development in the world (source: <http://data.stats.gov.cn/and> [9]).

Appendix B

Appendix B.1. Crop Residue Economic Value

Table A1. Cost table for crop residue collection process [67].

Category	Agricultural Machinery Capital Recovery	Operation and Maintenance Costs	Human Resources Cost	Management Fees	Corn Straw Price
Unit price(\$/t)	3.0	6.9	2.9	1.1	22.85
Total corp residue economic value (million USD)				318	

Appendix B.2. Excrements Economic Value

Table A2. Economic value of excrements [28].

Category	Biogas
Unit price (\$ USD/m ³)	1.047
Total cattle excrement economic value (million USD)	7400
Total excrement economic value (million USD)	3261

Appendix B.3. Economic Feasibility of the Available Biomass

Economic feasibility is the core problem of biomass energy development and utilization in China. An economic feasibility study is a kind of gain and loss comparison study. The comparison of gain and loss is a specific quantitative comparison. This paper cannot clearly define the specific evaluation object. Therefore, economic feasibility is only a structural argument rather than a specific computational analysis. Economic feasibility analysis includes the following three aspects of analysis.

(1) Economic feasibility of the operator

From the perspective of operators, the economic feasibility of the development and utilization of biomass energy sporadic production activities is mainly considered as follows: cash inflows including product sales revenue, state financial support and related subsidies and outflows including own capital investment, raw material acquisition costs, processing costs, storage and transportation costs,

and risks. Due to inadequate scale, inaccurate product positioning, weak market demand, and high risks, the economic feasibility of risks is mainly dependent on direct state investment, which can quickly turn sporadic production into a prairie fire, shortening the process from project construction to industrial development.

(2) Economic feasibility of local project construction

Generally speaking, the economic feasibility of this type is based on the economic feasibility of the project itself. As long as the project has good economic benefits, it is conducive to the development of local economy, increasing tax revenue, expanding employment, and increasing economic aggregate. The economic feasibility calculation should be carried out in accordance with the criterion of project economic evaluation (financial evaluation). First, cash inflow includes product sales revenue, recovery of fixed assets balance, recovery of working capital, and national financial transfer payments. Second, cash outflow includes the construction investment of processing enterprises, raw material acquisition costs, processing costs, storage and transportation costs, and tax payment. Third, it includes the calculation of relevant indicators and the economic evaluation of certainty and uncertainty.

It must be pointed out that the economic feasibility of the project cannot be generalized, and different conclusions may be drawn according to the specific project. The proposed project is the result of the economic feasibility study and is an economically feasible project.

(3) Economic feasibility of industrial development of national

At the national level, the formation and development of the biomass energy industry has great economic significance for China. First, it can ease energy pressure and improve the energy structure. Second, it may increase national income. Third, meeting the emission reduction requirements will result in substantial economic compensation. Fourth, it will result in reduced environmental pressure and reduce the social cost of environmental protection. Fifth, turns waste into a valuable resource and make rational use of energy. Of course, the development of the biomass energy industry also needs national support. The country also has to pay a certain cost, including price subsidies, tax relief, and energy restrictions. As long as the intensity is appropriate, the development of the biomass energy industry is economically rational and feasible.

Appendix C

Appendix C.1. Range of Straw/Grain Ratio

Table A3. Range of straw/grain ratio [19,77].

Crops	Range of Straw/Grain Ratio
Rice	0.75–1.5
Wheat	1.1–2.57
Maize	0.55–1.1
Legumes	1.25–1.5
Potato	0.2–1
Peanut	NA ^a
Rapeseed	1.25–2
Cotton	1.4–5.51
Sugar beet	0.2–0.25
Tobacco	NA ^a

^a Means none available.

Appendix C.2. Range of Collection Coefficient

Table A4. Range of collection coefficient [19].

Crops	Range of Collection Coefficient
Crops	0.75–0.9
Livestock excretion	0.6–0.9
Municipal solid waste	0.9

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