

Quantitative Estimation of Biomass Energy and Evaluation of Biomass Utilization - *A Case Study of Jilin Province, China*

Junnian Song¹, Wei Yang¹, Helmut Yabar¹ & Yoshiro Higano¹

¹ Graduate School of Life and Environmental Sciences, Tsukuba University, Tsukuba, Japan

Correspondence: Song Junnian, Graduate School of Life and Environmental Sciences, Tsukuba University, 1-1-1 Tennodai, Tsukuba, Ibaraki 305-8572, Japan. Tel: 81-80-3365-3120. E-mail: duliry@163.com

Received: April 8, 2013 Accepted: April 30, 2013 Online Published: May 30, 2013

doi:10.5539/jsd.v6n6p137

URL: <http://dx.doi.org/10.5539/jsd.v6n6p137>

Abstract

Jilin Province, as a large agricultural province, has abundant reserve of biomass resources. At the same time Jilin Province is currently suffering from energy shortage. Besides, consumption of conventional fossil fuels has resulted in the exacerbation of global warming and air pollution. Biomass energy as a renewable and substitutive energy, can mitigate the energy crisis and global warming, and improve environmental quality once it is fully utilized. This paper estimated the supply potential of biomass energy and integrated LCA and environmental cost analysis to make evaluation on biomass utilization taking biomass power generation system as example. Acquirable and utilizable amount of biomass energy in Jilin Province is equivalent to 21.26 tce, which can be accounted for 25.6% of total energy consumption in Jilin Province in 2011. Among all biomass energy, 59.1% comes from straw and agricultural residues, followed by 33.8% from livestock manure. According to the LCA results, total environmental impact of biomass power generation system is 0.721, much smaller than 25.321 of thermal power generation system. General cost of biomass power generation is higher, however its environmental cost is much lower than thermal power generation system (396 yuan/10⁴kWh < 1819 yuan/10⁴kWh). The results showed that biomass utilization has better environmental advantages and has the potential for the mitigation of energy crisis in Jilin Province.

Keywords: biomass energy, supply potential, biomass power generation, LCA, environmental cost

1. Introduction

With the increasingly depletion of conventional and non-renewable energy sources, research on biomass energy, which is a kind of renewable, abundant and environmentally friendly substitutive energy has been a hot issue around the world. Biomass energy is a kind of energy form that converts from solar energy to chemical energy through photosynthesis of green plants directly or indirectly and stored inside biomass (Wang & Ai, 2006).

Jilin Province, located in the northeast of China, is important industrial base and commodity grain base of China. Along with the acceleration of industrialization and urbanization, energy consumption of Jilin Province is increasing rapidly. Shortage of primary energy, low energy self-sufficiency rate and unreasonable energy structure are urgent problems for Jilin Province to solve. Besides, consumption of conventional fossil fuels has resulted in the exacerbation of global warming and air pollution. Reserve of primary energy of Jilin Province only accounts for 0.3% of China and its energy self-sufficiency rate is less than 50% (Zhao, 2011). Energy consumption is increasing continuously and there is large disparity between energy production and consumption. Figure 1 shows energy production and energy consumption of Jilin Province from 2000 to 2010. In 2010, conventional fossil energy accounted for 94.1% of the total energy consumption and new and renewable energy only accounted for 5.9%. Figure 2 shows the consumption ratio of different kinds of energy.

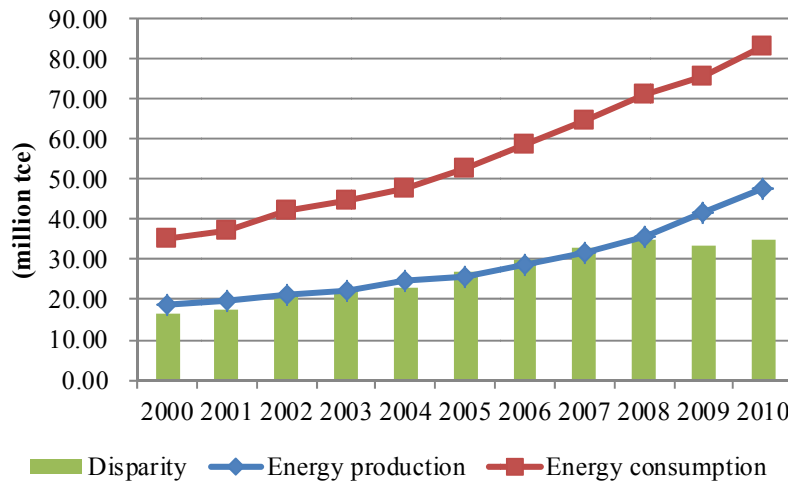


Figure 1. Energy production and consumption of Jilin Province from 2000 to 2010

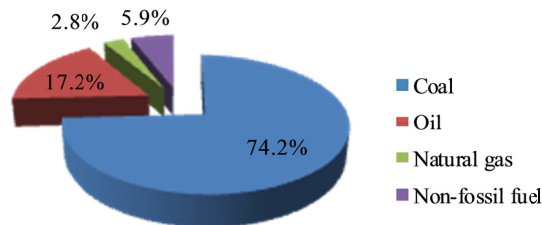


Figure 2. Energy consumption structure of Jilin Province in 2010

As a traditional agricultural province, there are a lot of advantages to support the biomass energy development in Jilin Province. Jilin Province has abundant reserve of biomass resources. Wide arable land, high yield of grain, scaled breeding and forestry industries are providing material basis for the utilization of agroforestry residues and livestock manure. According to the 12th 5-year plan, Jilin Province has proposed a target to raise the biomass energy production to 8.4 million tons of standard coal. The utilization of biomass energy can not only substitute conventional fossil energy to mitigate the energy crisis but also adjust the energy consumption structure to reduce the emission of green house gases and air pollutants.

Currently, domestic and foreign researches regarding evaluation of biomass energy utilization focus on benefit evaluation and policy support of different biomass energy industries. New Energy and Industrial Technology Development Organization of Japan published White-book of Renewable Energy Technologies introducing the biomass resource development potential in Japan and advanced biomass energy technologies (NEDO, 2010). Wang established the lumped weighted evaluation model based on Analytic Hierarchy Process and selected nine evaluation indexes to determine the major affecting factors of biomass utilization (Wang, 2008). Ren established a comprehensive evaluation index system based on non-linear programming for the utilization efficiency of agricultural biomass resources (Ren, 2011). Wenisch firstly analyzed the effect of biomass household biogas to household energy consumption and then analyzed the environmental benefit, economic benefit and social benefit of household biogas with LCA when evaluating the resource benefit of rural waste utilization in Denmark (Wenisch & Rousseaux, 2004). Thornley and Cooper analyzed the obstacles of biomass energy utilization especially the lack of legislation, economic elements, pricing without consideration of environmental impacts (Thornley & Cooper, 2008). Few research has been focused on empirical quantitative analysis on biomass utilization and its environmental effects to a specific region.

This article is aimed to estimate the biomass energy potential of Jilin Province quantitatively to show its mitigation capacity for energy shortage and determine the major utilization direction of biomass energy in Jilin Province. Based on the supply potential of biomass energy, evaluation of the environmental impacts and environmental cost of biomass utilization through LCA will be made to show the environmental advantages of

biomass energy compared with conventional energy taking biomass power generation system in Jilin Province as example.

2. Materials and Methods

2.1 Quantitative Estimation of Biomass Energy Potential

There are different indexes for the availability evaluation of biomass energy and the amount calculation of organic biomass resources in corresponding to different criterion (Li, Ren, & Zhuang, 2001). Here three definitions including physical reserve, acquirable and utilizable amount, and equivalent of standard energy are introduced (Liu & Shen, 2007). The amount of major biomass resources is evaluated step by step according to these three definitions.

2.1.1 Physical Reserve

Physical reserve is the total amount of theoretically physical production of major biomass resources from four sources including straw and agricultural residues, firewood and forestry residues, livestock manure and municipal waste.

(1) Straw and agricultural residues

Straw and other agricultural residues mainly come from food crops, cotton, hemp and sugar. Straw-grain ratio method is widely adopted to calculate the amount of crop straw. Straw-grain ratio is the ratio of the amount of stems above the ground and the amount of economic yield of crops. The yield of straw can be calculated by:

$$CR = \sum_{i=1}^n Qc_i \times r_i \quad (1)$$

CR: physical amount of straw, Qc_i : yield of Crop i , r_i : straw-grain ratio of Crop i . Straw-grain ratios of different crops are shown in Table 1 (Liu, Na, & Wang, 2010; Bi, 2010).

Table 1. Straw-grain ratio of different crops

Crops	Rice	Wheat	Corn	Sorghum	Soybean	Sunflower	Hemp
Ratio	1	1.3	1.32	1.6	1.16	2.8	2

(2) Firewood and forestry residues

Forestry biomass resources mainly derive from clearing, cutting and processing residues of forestry production, firewood forests and forest tending and thinning. The amount of forestry biomass resources can be calculated either with index as area of forests, firewood coefficient and production of per unit area (Yuan, Wu, & Huang, 2002) or by respectively calculating the amount of firewood forests, residues of forestry production and other forestry biomass (Research Group of Chinese Forest Bio-energy [RGCFB], 2006). This article mainly calculates the amount of forestry residues, firewood forests, forest tending and thinning and the adjacent small trees by:

$$FR = \sum_{i=1}^n Qf_i \times r_i \quad (2)$$

FR: physical amount of forestry biomass, Qf_i : amount of Forestry biomass i , r_i : conversion coefficient. Some related conversion coefficients are shown in Table 2 (Yuan et al., 2002; RGCFB, 2006; Shi, 2008).

Table 2. Conversion coefficients of different forestry biomass

Forestry biomass	Cutting residues	Processing residues	Firewood forests	Forest tending and thinning	Adjacent small trees
Coefficient	40% of the cutting amount	40% of the log amount	100%	100%	100%
Weight conversion	1.17 t/m ³	0.9 t/m ³	50 m ³ /hm ² , 1.17 t/m ³	8 m ³ /hm ² , 0.9 t/m ³	2 kg/per plant

(3) Livestock manure

The amount of manure is related to species, breeds, genders, growing season and so on (Ding, 2000). Here the livestock is assumed as mature and the breeding cycle is assumed as fixed. The amount of manure can be calculated with daily yields and breeding cycle by:

$$D = \sum_{i=1}^n Qd_i \times d_i \times m_i = \sum_{i=1}^n Qd_i \times M_i \quad (3)$$

D: physical amount of manure, Qd_i : the number of Livestock i , d_i : daily yield of dry manure of Livestock manure i , m_i : breeding cycle, M_i : manure yield of Livestock i within the whole breeding cycle. Breeding cycle and manure yield of different livestock and poultry are shown in table 3 (Liu & Shen, 2007; Ding, 2000; Wang, 1998; Peng & Wang, 2004).

Table 3. Breeding cycles and manure yields of different livestock and poultry Unit: day and kg

Livestock	Hogs	Herds hogs	Cattle	Cows	Sheep	Horse	Jennets	Poultry
Breeding cycle	300	365	365	365	365	365	365	55
Manure yields	1050	1460	8200	21900	632	5237	3092	4.5

(4) Municipal waste

Municipal waste consists of municipal solid waste and municipal waste water. Municipal solid waste can be divided into organic waste and inorganic waste according to the composition. The organic waste can be utilized as biomass resources. Municipal waste water is divided into domestic sewage and industrial wastewater, both can be treated to produce biogas. The amount of total municipal waste can be calculated by:

$$MW = SW \times r_1 + QW \times r_2 \quad (4)$$

SW: the amount of municipal solid waste, r_1 : the percentage of organic waste from municipal solid waste, QW: the amount of waste water, r_2 : the percentage of COD in waste water.

2.1.2 Acquirable and Utilizable Amount

Physical reserve of biomass resources is the amount representing the theoretically richest developing potential (LIU & SHEN, 2007). Not all the reserve can be acquired and utilized to produce energy. There is availability coefficient and utilization coefficient of biomass resources for energy generation. The acquirable and utilizable amount refers to the amount of biomass resources that can be acquired and utilized to produce energy under theoretical conditions. It can be calculated from the amount of physical reserve.

$$CR' = \sum_{i=1}^n Qc_i \times r_i \times \lambda_i \times \delta_i \quad (5)$$

CR': acquirable and utilizable amount of straw, λ_i : availability coefficient of Crop i . δ_i : utilization coefficient. Acquirable and utilizable amount of forestry residues (FR'), livestock manure (D') and municipal waste (MW') can be calculated with corresponding λ_i and δ_i . Availability coefficient of all kinds of biomass resources is the collection ratio and determined according to local conditions and the average value will be adopted. The ratio of straw amount utilized as household fuel and discarded or combusted can be considered as energy production and is determined as 80%. About 1/3 of forestry residues and livestock manure can be utilized to produce energy. About 60% of municipal solid waste can be utilized through combustion and compost. About 50% of municipal waste water can be utilized to produce biogas. Table 4 concludes the availability coefficient and utilization coefficient of different biomass resources (Liu & Shen, 2007; Liu et al., 2010; RGCFB, 2006; Yuan, Wu & Ma, 2005; National Development and Reform Commission-Energy Research Institute [NDRCERI], 2010; Milbrandt, 2005).

Table 4. Availability coefficient and utilization coefficient of different biomass resources (λ_i and δ_i)

Types	Straw	Forestry residues	Livestock manure	Municipal solid waste	Municipal waste water
Availability coefficient(λ_i)	90%	40%	60%	40%	100%*
Utilization coefficient (δ_i)	80%	1/3	1/3	60%	50%

*The data of the amount of municipal waste water collected from statistical year book can be considered as the acquirable amount, therefore the availability coefficient is determined as 100%.

2.1.3 Equivalent of Standard Energy

When put into unified and practical studies, biomass energy is usually accounted to the equivalent of standard energy, which is generally standard coal equivalent. In terms of the calculation of straw standard energy (ECR), conversion coefficient η_i is introduced into the calculation as:

$$ECR = \sum_{i=1}^n Qc_i \times r_i \times \lambda_i \times \delta_i \times \eta_i \quad (6)$$

As for the calculation of forestry residues standard energy equivalent (EFR), livestock manure standard energy equivalent (ED) and municipal waste standard energy equivalent (EMW), corresponding η_i should be introduced. When waste water is converted to standard energy equivalent, it is firstly converted to biogas (0.907 m³ biogas can be generated from 1 kg COD) (Milbrandt, 2005). Table 5 concludes conversion coefficient of different types of biomass resources (Liu & Shen, 2007).

Table 5. Conversion coefficient of standard energy of different biomass resources(η_i) Unit: biogas, kgce/m³; others, kgce/kg

Types of livestock and poultry	Coefficient
Rice straw	0.429
Wheat straw	0.500
Corn straw	0.529
Sorghum straw	0.050
Soybean straw	0.543
Sunflower straw	0.529
Hemp straw	0.500
Firewood	0.571
Hog manure	0.429
Cattle manure	0.471
Poultry manure	0.643
Horse, sheep and jennet manure	0.529
Municipal solid waste	0.143
Biogas	0.857

2.2 Life Cycle Environmental Impact Assessment of Biomass Power Generation System

Life Cycle Assessment (LCA) is a tool used to assess the impacts on environment brought by products or conduct during the life cycle. LCA can identify and quantify the utilization of energy and materials and the emission of wastes; assess the impact extent of the utilization and emission and strive to seek the chance to improve the environmental quality (Liu & Wang, 2008).

This part is a case study that associates LCA and cost analysis to make comprehensive evaluation on biomass utilization taking a biomass power generation system in Jilin Province as example.

2.2.1 Introduction of Biomass Power Generation System

(1) Introduction of the study object

Songyuan City is a new petrochemical city located in the west of Jilin Province. It is large commodity grain base and oil base of China whose yield of corn is 4 million ton, accounting for 1/4 of Jilin Province's total yield. The government deployed the overall route of straw power generation to construct Datang Songyuan biomass power generation project in Songyuan City to develop and promote biomass utilization.

The study object of this research is 15MW (2 sets) straw direct-fired power generation system, whose annual electricity generation time is 6000 h and rated annual generating capacity is 1.8×10^8 kWh. Environmental impacts brought by 10000 kWh of power generation will be calculated and analyzed, which means the functional unit of the system is 10000 kWh. Main processes of the system include feedstock collection, straw combustion, water recycling and purification, and power generation.

(2) Sources of straw

There are 0.76 million hm^2 of farmlands in Songyuan City. Total yield of corn in normal year is 5 million ton. Within the scope of 25 km radius, yield of corn straw is 0.691 million t/a, of which 65% is discarded. Calculated by this proportion, corn straw that can be used as fuel for power generation is 0.449 million t/a.

Table 6. Straw consumption of the plant

Boiler	Consumption per hour (t/h)	Consumption per day (t/d)	Consumption per year (10^6t/a)
1×75t/h	17.0	374.0	0.102
2×75t/h	34.0	748.0	0.204

Table 6 shows straw consumption of the plant. Fuel demand of the plant is 0.204 million t/a. So the supply amount can satisfy the fuel demand of the power generation system.

2.2.2 Assessment Scope and Boundary Demarcation

When determining the assessment boundary, some points should be considered: (1) In order to form a closed loop system, the coal, oil, electricity, steel and water consumed during construction period of the plant are not involved into the boundary; (2) Because biomass power generation system is a new system that has not reached the scrapping age, equipment recovery unit is not considered. (Liu, 2010) Based on the assumptions above, biomass power generation system can be divided into three parts: (1) Agricultural production period; (2) Transportation period; (3) Plant operational period. Figure 3 shows the life cycle boundary and frame of the power generation system.

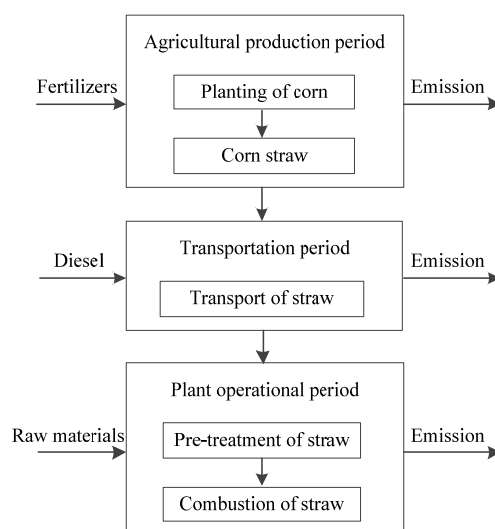


Figure 3. Life cycle boundary and frame of the power generation system

2.2.3 Inventory Analysis

Inventory analysis is to quantify and assess the processes of energy and resources consumption and environmental release during life cycle of the system. The raw materials and energy consumed is determined as input inventory and the substances (including waste gases, waste water and solid waste etc.) emitted into environment from all processes of the system is determined as output inventory.

(1) Agricultural production period

Emissions from agricultural production has three sources: (1) Pollutant emission from mechanical use; (2) Pollutant emission from fertilizer use; (3) Emission of nitrogen fertilizer loss due to inefficient use of fertilizers. In life cycle inventory analysis, there should be distribution of energy flow and pollutant emission for the system that has various kinds of output. During planting process of corn, straw is by-product. According to the economic value, energy consumption and pollutant emission of corn straw account for 10% of the whole energy flow and pollutant emission of the planting process of corn. Calculated by this proportion, emission amount of pollutants from corn straw consumed by the plant in one year can be obtained and shown in Table 7 (Liang, Chen, & Gao, 2009).

Table 7. Emission amount of pollutants during agricultural production period

Unit: t/a

Pollutants	CO ₂	CO	CH ₄	N ₂ O	NO _x	Dust	SO ₂
Emission amount	13916.88	33.72	10.98	4.96	63.51	0.18	125.62

(2) Transportation period

The transportation radius is within 25km. 9 collection stations will be established around the power generation plant. Because the binding of straw is mostly done manually, consumption of this period is mainly fuel consumption of transportation tools. Pollutant emission is mainly from exhaust of diesel vehicles. According to the distances between collection stations and the plant, average transportation radius can be determined as 25 km and the transportation tool is determined as agricultural diesel vehicle whose load is 5 ton. Emission amount of pollutants during transportation period can be calculated with diesel consumption and emission coefficient. The results are shown in Table 8 (Hu, 2006).

Table 8. Emission amount of pollutants during feedstock transportation period

Pollutants	CO	Dust	NO _x	SO _x	CO ₂	CH ₄	N ₂ O
Emission coefficient (g/GJ)	435.651	16.337	762.390	93.665	73623.755	5.870	2.929
Emission amount(t/a)	21.87	0.82	38.27	4.70	3695.91	0.29	0.15

(3) Plant operational period

During plant operational period, diesel is the major combustion accelerant and electricity is consumed. Pollutants including waste gases, waste water and solid waste are from the following production links:

Table 9. Pollutant generation links of plant operation

Types of pollutants		Source	Major pollutants	Discharge pattern	Disposition
Waste gases	Boiler gases	Straw combustion	SO ₂ , NO _x , HCL, dust	Continuous	Atmosphere
	Recycling sewage	Circular cooling system	Salts, COD	Continuous	Direct reuse
Waste water	Acid-alkali waste water	Chemical treatment	pH, COD	Discontinuous	Municipal pipe after treatment
	Boiler sewage	Boiler cleaning	pH, salts, SS	Discontinuous	Circular system after treatment
	Industrial waste water	Pump cooling	Oil, SS	Continuous	Circular system after treatment
Solid waste	Straw ashes	Boiler	Solid waste	Discontinuous	Fertilizer production

Table 10. Types and emission amount of the waste gases during plant operational period

Emission index	SO ₂	NO _x	Dust	HCL
Concentration (mg/m ³)	226.225	400	23.135	52
Amount (t/a)	250.614	443.124	25.629	57

Types of waste gases and emission amount are shown in Table 10. Waste water from all discharge links is either reused or discharged into municipal pipe network after treatment. The discharge concentration can reach the standard and has little impact on environment. So when calculating environmental impact potential, water environmental impacts can be neglected. Wangsheng Fertilizer Company will purchase all the straw ashes to produce organic fertilizers. So all the ashes will be reused and their environmental impacts can be neglected.

(4) Inventory summary

Considering the close carbon cycle, here is a crucial premise that the amount of CO₂ generated during plant operational period is equivalent to that absorbed by corn during growing process (Zhang, 2002). What brings impacts to environment is mainly air pollutants. According to the annual emission amount of pollutants and the annual amount of electricity generation, emission amount of pollutants of 1 functional unit can be calculated as is shown in Table 11.

Table 11. Inventory of life cycle emission of biomass power generation system per functional unit Unit: kg/10⁴kWh

Pollutants	Agricultural production period	Transportation period	Plant operational period	Total amount
CO ₂	773.160	205.328	0.000	978.488
CO	1.873	1.215	0.000	3.088
CH ₄	0.610	0.016	0.000	0.626
N ₂ O	0.276	0.008	0.000	0.284
NO _x	3.528	1.826	24.618	29.972
Dust	0.010	0.046	1.479	1.535
SO ₂	6.979	0.261	13.923	21.163

2.2.4 Calculation of Environmental Impact Potential

This part will quantify environmental impacts brought by energy consumption and pollutant emission of the power generation system to lay the foundation of evaluation and improvement of the system. According to the life cycle inventory, five environmental impacts caused by the pollutant emission including Global Warming, Acidification, Photochemical Ozone Creation, Health Toxicity and Solid Waste will be analyzed.

(1) Environmental impact potential

Environmental impact potential refers to the sum of all the impacts of similar pollutant emission within the system. Similar pollutants can be converted to reference's environmental impact potential with equivalent coefficient. Calculation formula of environmental impact potential is:

$$EP(m) = \sum EP(m)n = \sum [Q(m)n \times EF(m)n] \quad (7)$$

EP(m): Environmental impact potential m, EP(m)n: Environmental impact potential m of Pollutant n, Q(m)n: emission amount of Pollutant n, EF(m)n: coefficient of Environmental impact potential m of Pollutant n.

(2) Standardization

Standardization of data is to make environmental impact potential dimensionless. The standardized data can intuitively and exactly reflect the environmental impacts of the biomass power generation system. This article chooses the environmental impact potential per capita of the whole society in 1990 as the norm of the standardization. According to the concept of standard human equivalent (the environmental impact potential caused by per capita annually) established by Yang Jianxin (Yang, Xu, & Wang, 2002), the unit of normalized environmental impact potential is standard human equivalent ($PE_{China, 1990}$). The calculation formula is:

$$NP(m) = EP(m) / ER(m) \quad (8)$$

NP(m): Standardized environmental impact potential m, EP(m): Environmental impact potential m of the system, ER(m): standardization norm. Standardization norm of environmental impacts is shown in Table 12.

Table 12. Standardization norm of environmental impacts

Environmental impact potential	Standardization norm
Global Warming Potential (GWP)	8700 kgCO ₂ eq
Acidification Potential (AP)	36 kgSO ₂ eq
Photochemical Ozone Creation Potential (POCP)	0.65 kgC ₂ H ₄ eq
Health Toxicity Potential (HTP)	18 kg
Solid Waste Potential (SWP)	18 kg

(3) Weighted assessment

Standardization cannot compare the relative seriousness of different environmental impacts. It is necessary to make the sequence of the seriousness of different environmental impact potential by endowing different weights to the extent of environmental damage. The calculation formula is:

$$WP(m) = WF(m) \times NP(m) \quad (9)$$

WP(m): Weighted environmental impact potential m, WF(m): weight of Environmental impact potential m, NP(m): Standardized environmental impact potential m.

This paper mainly analyzes five environmental impacts and adopts Analytic Hierarchy Process (AHP) to analyze the relative importance of the five environmental impacts to determine the weights of them. The judging matrix of nine-scale analysis is adopted as is shown in Table 13.

Table 13. The judging matrix of nine-scale analysis

a_{ij}	Global Warming	Acidification	Photochemical Ozone Creation	Health Toxicity	Solid Waste
Global Warming	1	3	6	5	4
Acidification	1/3	1	5	3	3
Photochemical Ozone Creation	1/6	1/5	1	1/4	1/2
Health Toxicity	1/5	1/3	4	1	2
Solid Waste	1/4	1/3	2	1/2	1

According to the judging matrix,

$$q_{ij} = a_{ij} / \sum_{k=1}^m a_{kj} \quad (10)$$

$$\alpha_i = \sum_{j=1}^m q_{ij} \quad (11)$$

$$w_i = \alpha_i / \sum_{k=1}^m \alpha_k \quad (12)$$

$$\lambda_{\max} = \frac{1}{m} \sum_{i=1}^m \frac{(AW)_i}{w_i} \quad (13)$$

The weight vector is $W=(w_1, w_2, \dots, w_m)^T = (0.48, 0.25, 0.05, 0.13, 0.09)^T$. The largest eigenvalue is $\lambda_{\max} = 5.222$.

$$CI = \frac{\lambda_{\max} - m}{m - 1} \quad (14)$$

The Consistency Index, CI can be calculated as 0.056. The Random index, RI is 1.13 according to random index table. The Consistency Rate, $CR=CI/RI=0.0459<0.1$ (according to average random consistent index, when $m \geq 3$, $CR < 0.1$, consistency can meet the requirement), so the consistency can be accepted.

2.3 Life Cycle Cost Analysis

In order to stress the environmental advantages of biomass power generation system, this article calculates the external environmental cost of biomass power generation system and involves it into life cycle cost analysis.

(1) General cost analysis

General cost mainly consists of the consumption cost of raw materials and energy, operational cost, transportation cost, investment cost, depreciation cost and tax cost. Table 14 shows the economic evaluation of biomass power generation system.

Table 14. Economic evaluation of biomass power generation system

Items	Unit	Value
Total investment	10 ³ yuan	288,730
Static investment	10 ³ yuan	255,300
Dynamic investment	10 ³ yuan	266,670
Operation years	years	20
Operation time	h/a	6,000
Total electricity generation	GWh	211
Price of corn straw	yuan/t	250
Quantity of corn straw	10 ³ t	204
Fuel cost	10 ³ yuan	51,000
Labor cost	10 ³ yuan	4,000
Maintenance cost	10 ³ yuan	6,000
Materials cost	10 ³ yuan	12,000
Management cost	10 ³ yuan	1,500
Depreciation cost	10 ³ yuan	15,000

(2) Environmental cost analysis

External environmental cost of biomass power generation system refers to the value converts from the impacts caused by pollutants during the whole life cycle. The conversion is according to current environmental costs of all kinds of pollutants. Taking reference of the Pollution Charge Standard (PSC) of China and the Environmental Value Standard of the USA (U.S.EVS) (Huang, 2008), the standard measurement of environmental value of different pollutants can be shown in Table 15.

Table 15. Standard measurement of environmental value

Unit: yuan/kg

Pollutant	CO ₂	CO	NO _x	SO ₂	PM ₁₀
Environmental value	0.023	1	8	6	2.2

The calculation formula is:

$$LCEC = \sum Q(n) \times EV(n) \quad (15)$$

LCEC: Life cycle environmental cost, Q(n): emission amount of Pollutant n, EV(n): Environmental value of Pollutant n.

3. Results and Discussion

3.1 Results of Biomass Energy Potential in Jilin Province

With the calculation analysis and data summary (collected from Statistical Yearbook of Jilin Province 2011), results of physical reserves, acquirable and utilizable amount and equivalent of standard energy are obtained and shown in Table 16.

Table 16. Results summary of organic biomass energy in Jilin Province

Types	Physical reserves (10 ⁶ t)	Acquirable and utilizable amount (10 ⁶ t)	Standard energy equivalent (10 ⁶ tce)	Percentage
Straw and agricultural residues	35.04	25.23	12.58	59.1%
Firewood and forestry residues	11.00	1.47	0.84	3.9%
Livestock manure	78.01	15.60	7.19	33.8%
Municipal waste	5.58	3.29	0.66	3.1%
In total	129.63	45.59	21.26	100%

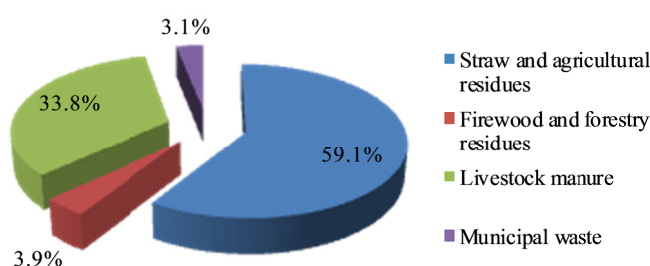


Figure 4. Amount composition of various biomass energy

The results show that total amount of biomass energy in Jilin Province is 21.26 million tce, among which 59.1% comes from farming, 33.8% comes from animal husbandry, 3.9% comes from forestry and 3.1% comes from city. The total amount of biomass energy can be accounted for 25.6% of total energy consumption of Jilin Province in 2011. Compared with the disparity of energy production and consumption in 2010 in Jilin Province (35.07 million tce), once the biomass energy is fully developed and utilized, it can facilitate to the mitigation of severe energy crisis in Jilin Province. Farming is the biggest source of biomass energy in Jilin Province providing a advantageous condition for the utilization of straw. So there should be a priority for the utilization of straw and agricultural residues.

3.2 Life Cycle Environmental Impact Assessment of Biomass Power Generation System

3.2.1 Results of Environmental Impact Potential

Calculation results of all life cycle environmental impact potential, standardization results and weighted assessment results are shown in Table 17 to Table 19.

Table 17. Results of life cycle environmental impact potential

Environmental impact potential	Pollutants	Equivalent coefficient	Agricultural production period	Transportation period	Plant operational period	In total
GWP (kgCO ₂ eq)	CO ₂	1	880.334	210.828	0.000	1091.162
	CO	2				
	CH ₄	25				
	N ₂ O	320				
AP (kgSO ₂ eq)	NO _x	0.7	9.449	1.539	31.155	42.143
	SO ₂	1				
POCP (kgC ₂ H ₄ eq)	CO	0.03	0.060	0.037	0.000	0.097
	CH ₄	0.007				
HTP (kg)	CO	0.012	11.149	1.752	35.909	48.811
	NO _x	0.78				
	SO ₂	1.2				
SWP (kg)	Smoke&dust	1	0.010	0.046	1.479	1.535

Table 18. Standardized results of life cycle environmental impact potential

	Environmental impact potential	Agricultural production period	Transportation period	Plant operational period	In total
	GWP	0.101	0.024	0.000	0.125
	AP	0.262	0.043	0.865	1.171
	POCP	0.092	0.057	0.000	0.149
	HTP	0.619	0.097	1.995	2.712
	SWP	0.001	0.003	0.082	0.085

Table 19. Weighted assessment results of life cycle environmental impact potential

Environmental impact potential	Weight	Agricultural production period	Transportation period	Plant operational period	Weighted results
GWP	0.48	0.049	0.012	0.000	0.060
AP	0.25	0.066	0.011	0.216	0.293
POCP	0.05	0.005	0.003	0.000	0.007
HTP	0.13	0.081	0.013	0.259	0.353
SWP	0.09	0.000	0.000	0.007	0.008
In total	1	0.199	0.038	0.483	0.721

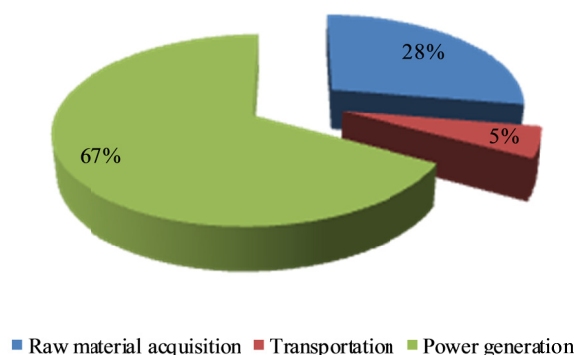


Figure 5. The share of environmental impacts from different processes

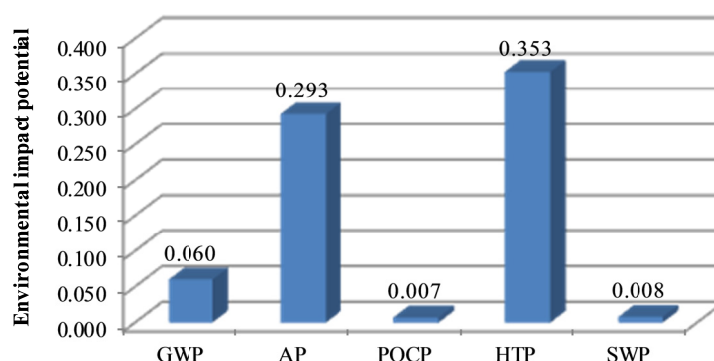


Figure 6. Weighted assessment results of life cycle environmental impact potential

3.2.2 Analysis and Discussion About Life Cycle Assessment

(1) Improvement assessment of life cycle

As is shown in Figure 5, among three processes of the whole system, power generation brings the most environmental impacts. When selecting the plant address, because of the consideration of fuel acquisition, all the collection stations supplying corn straw are near to the plant, which contributes to fewer impacts of transportation process. During agricultural production period, this article makes distributions of energy input and pollutant emission in agricultural production period according to the economic value. Because the distribution proportion is determined as 10% that is not so large, it does not bring substantial environmental impacts to involve the planting of corn straw into the life cycle boundary.

Among all the environmental impacts, Health Toxicity and Acidification which results from the emission of CO, NO_x and SO₂ account for larger proportion. Even though low-nitrogen combustion technology has already been adopted and the height of exhaust pipe has been augmented, environmental impacts are still notable. Besides, the use of fertilizers during straw plating period contributes to the emission of NO_x and SO_x. Taking into consideration of carbon cycle of biomass, namely the neglect of CO₂ emitted by straw combustion during power plant operational period, greenhouse gases of biomass power generation system mainly come from agricultural production period and transportation period. Photochemical Ozone Creation and Solid Waste are endowed with small weights and the pollutants don't have high concentration, leading to fewer impacts. Therefore when improving environmental impacts, the technologies and measures to lower the concentration of CO, NO_x and SO₂ should be focused on to reduce the impacts of health toxicity and acidification.

(2) Comparison with thermal power generation system

Taking reference to the research of LCA on thermal power generation system (the calculation of pollutant emission and energy consumption on average level of China) done by Di Xianghua and Nie Zuo (Di & Nie,

2005), the emission amount of pollutants of thermal power generation system by generating 10000kWh electricity can be obtained and the environmental impacts brought by the pollutants can be calculated.

Table 20. Emission amount of pollutants of thermal power generation system

Unit: kg/10⁴kWh

Pollutants	CO ₂	SO ₂	NO _x	CO	CH ₄	Dust
Emission amount	10700	99.3	64.6	15.5	26	202

Table 21. Weighted assessment results of life cycle environmental impact potential of thermal power generation system

Environmental impacts	Weight	Weighted results
GWP	0.48	1.768
AP	0.25	20.072
POCP	0.05	1.245
HTP	0.13	1.226
SWP	0.09	1.010
In total	1	25.321

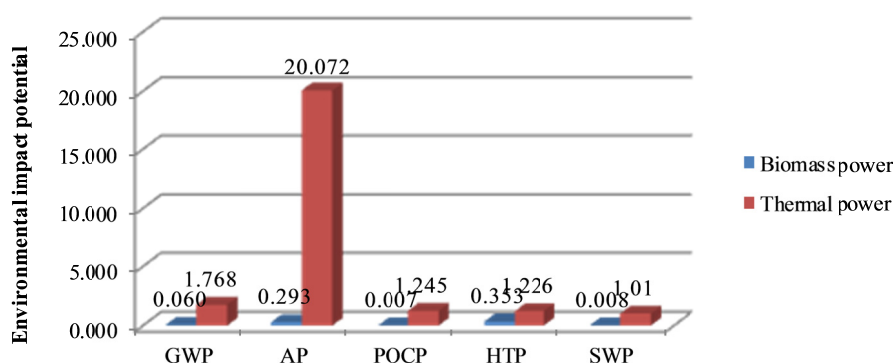


Figure 7. Comparison of environmental impacts of biomass power generation system and thermal power generation system

Illustrated by Figure 7, we can clearly see that total environmental impact burden of thermal power generation system is 25.321, which is much larger than 0.721 of biomass power generation system. Acidification potential is the largest due to the combustion of coal containing high amount of sulfur.

3.3 Life Cycle Cost Analysis of Biomass Power Generation System

3.3.1 General Cost Analysis

General cost of biomass power generation system mainly consists of fuel cost, staff salaries, maintenance cost, material cost, management cost and depreciation cost.

Table 22. Cost structure of biomass power generation system

Unit: yuan/10⁴kWh

Costs	Value
Fuel cost	2420
Labor cost	190
Maintenance cost	280
Materials cost	570
Management cost	70
Depreciation cost	710
Cost per 10 ⁴ kWh	4240

Cost structure of biomass power generation system shows that its general cost is 4240 yuan/10⁴kWh. Average general cost of thermal power generation system is 3250 yuan/10⁴kWh (Chinese Energy, 2012). Compared with thermal power generation system, the cost of biomass power generation system is higher. And among all the costs, fuel cost accounts for more than 50%. Several reasons are responsible for the high cost of biomass power generation system: (1) Higher investment in advanced equipments; (2) Lower electricity generation efficiency and high demand of fuels; (3) Higher transportation cost of fuels due to corn straw's large volume.

3.3.2 Environmental Cost Analysis

Table 23. Environmental cost account of biomass power generation system

Pollutants	Environmental value(yuan/kg)	Emission amount(kg/10 ⁴ kWh)	Environmental cost(yuan/10 ⁴ kWh)
CO ₂	0.023	978.488	22.5
CO	1	3.088	3.1
NO _x	8	29.972	239.8
SO ₂	6	21.163	127.0
PM ₁₀	2.2	1.535	3.4
In total			395.7

Table 24. Environmental cost account of thermal power generation system

Pollutants	Environmental value(yuan/kg)	Emission amount(kg/10 ⁴ kWh)	Environmental cost(yuan/10 ⁴ kWh)
CO ₂	0.023	10700	246.1
CO	1	15.5	15.5
NO _x	8	64.6	516.8
SO ₂	6	99.3	595.8
PM ₁₀	2.2	202	444.4
In total			1818.6

The results show that environmental cost of biomass power generation system is 395.7 yuan/10⁴kWh and environmental cost of thermal power generation system is 1818.6 yuan/10⁴kWh, which is much larger. Due to high amount of pollutants emission in transportation process of coal and the emission of high concentrations of SO₂ and NO_x in operational process of plant, thermal power generation system produces more serious impacts to environment that generates higher environmental cost.

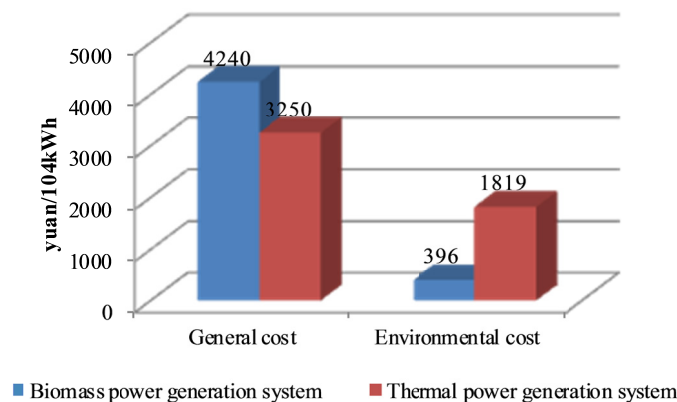


Figure 8. Comparison of life cycle cost of biomass power generation system and thermal power generation system

Compared with thermal power generation system, biomass power generation system has higher general costs however the environmental cost is much lower. When doing program investment, economic benefit is a key factor that affecting decision-making. Current evaluations of biomass power generation system mainly focus on economic benefit without taking environmental benefit into consideration. Since the internalization of external environmental cost is ignored, environmental advantages of biomass power generation system cannot be reflected compared with conventional thermal power generation system.

4. Conclusions

By estimating the biomass resources from four sources, this article obtained the total amount of biomass energy in Jilin Province, an amount that can be accounted for nearly 1/4 of total energy consumption in Jilin Province in 2011, which shows the potential of biomass utilization in mitigating the energy crisis. Farming is the biggest source of biomass energy in Jilin Province providing the major development direction of biomass industries.

With LCA of biomass power generation system, environmental advantages of biomass utilization is shown and proved compared with the utilization of conventional fossil energy. The comparison of general cost and environmental cost between biomass energy utilization and conventional fossil energy utilization further shows the environmental advantages of biomass utilization and the significance of internalization of environmental cost.

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