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Article

The Comparative Life Cycle Assessment of Power Generation from Lignocellulosic Biomass

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Abstract: In order to solve the energy crisis and reduce emissions of greenhouse gases (GHG), renewable energy resources are exploited for power generation. Because lignocellulosic biomass resources are abundant and renewable, various technologies are applied to using lignocellulosic biomass to derive biofuel and electricity. This paper focuses on power generation from lignocellulosic biomass and comparison of the effects of different feedstocks, transportation, and power generation technologies evaluated through life cycle assessment (LCA). The inputs and boundaries of LCA vary with different feedstocks, such as forestry wood, agricultural residues, and fast-growing grass. For agricultural residues and fast-growing grass, the transportation cost from field to power plant is more critical. Three technologies for power generation are analyzed both with and without pelletization of lignocellulosic biomass. The GHG emissions also vary with different feedstocks and depend on burning technologies at different plant scales. The daily criteria pollutant emissions of power generation from different lignocellulosic biomass were evaluated with a life cycle assessment model of GREET.net 2014. It is concluded that bio-power generation is critical with the urgency of greenhouse effects.

Keywords: life cycle assessment; lignocellulosic biomass; power generation; GHG emissions

1. Introduction

The United Nations has recently reported that global warming is mainly due to progressive consumption of fossil resources on the Earth [1]. The current energy consumption structure mostly depends on coal, oil, and natural gas for power generation and chemical productions in most countries and results in substantial emissions of greenhouse gases (GHGs) [1,2]. GHGs, such as CO_2, CH_4, O_3, and N_2O, play an important role in global climate change. The increase of GHG level changes the climate and further influences natural ecosystems, water resource distribution and agricultural production. In order to reduce the climate change, some efforts have been made to reduce the emission of GHGs. The United Nations proposed some policies and actions associated with energy consumption to limit net GHG emissions. The Kyoto Protocol agreed by numerous countries was another milestone. Some countries in America, Europe, and Asia started to widely consider different renewable energies as potential long-term sources of energy supply in the 1980s or even earlier. It has been reported that, starting from 2009, renewable energy has accounted for eight percent of the energy supply in the United States. Thus, renewable biomass plays a significant role in the energy supply in the world, especially in the United States.

Lignocellulosic biomass is widely distributed in the different forms, e.g., forestry, energy crops, and agricultural residues. Various technologies [3] have been developed to use lignocellulosic biomass in gasification, biofuel derivation, and electricity power generation. The gasification of wood or forestry residue was widely used when oil was deficient in World War II, but the technology was not efficient enough. Currently, many research resources are being put into biofuel generation, including bioethanol and biodiesel from various types of lignocellulosic biomass. The first generation of biofuel generation technologies have been successfully applied to corn, soybeans, sugarcane, and beets to extract bioethanol and biodiesel, however, this partially contributes to the increase of food price in the world. Starting from the 1990s, more efforts have been shifted to non-food lignocellulosic biomass, mainly from crop residues, switch grass, fast-growing wood, forest residues, *etc.* The second generation technologies for biofuel currently encounter many challenges at the experimental step, especially for bioethanol from the land-planted biomass. However, burning biomass to generate electricity and heat is relatively easy and has been widely used in some European countries since the 1990s and started from the pioneered plants in America and Asia in the 21st century.

Biomaterial constitutes the world's largest renewable resource for power generation. Lignocellulosic biomass resources available for power generation mainly include agricultural crop residues (such as wheat straw, corn stover, rice straw, and other cultured plant stems), wood and its wastes from forestry and industry (such as bough, bark, and sawdust), dedicated short-rotation energy coppice (such as eucalyptus, poplar, and willow), and grass (such as switch grass and other natural grasses). The renewable biomass generally includes three main components: cellulose, hemicellulose, and lignin; and cellulose and hemicellulose make up approximately 70% of the entire biomass [4,5].

Agricultural crop residues include 25%–35% hemicelluloses, 37%–50% celluloses, 5%–15% lignin, and 12%–16% ash; the compounds of grass, such as switch grass, are similar to agricultural crop residues; and wood residues including hard wood and soft wood are divided into 25%–40% hemicelluloses and 40%–47% cellulose, 20%–60% lignin, and a little amount of ash. This article focuses on the investigation of power generation from lignocellulosic biomass with different candidates, as well as the efficiency improvement for electricity and heat generation evaluated from life cycle assessment [6–10].

Life cycle assessment, also called life cycle analysis (LCA), evaluates the environmental burdens by identifying resource inputs, energy consumptions, and emissions to various environmental compartments resulting from the particular life cycle of a product. It commonly comprises of four steps, goal and boundary definition, inventory analysis, impact assessment, and impact interpretation. Here, different models of LCA are evaluated to clarify the environmental effects of different types of lignocellulosic biomass according to environmental impacts during the whole process of power generation through discussion of the energy, supply consumption and GHG emissions. The whole process starts from the biomass plantation and ends at waste releases in power plants.

2. Feedstock of Lignocellulosic Biomass and Preparations

2.1. Feedstocks from Forestry Wood and the Cultivation

Thirty percent of lignocellulosic biomass produced every year in the United States is forest woody feedstock and it is about 336 million tons [11]. Forest woody materials are generally classified into softwoods and hardwoods. Most softwoods grow faster and possess lower wood densities which generally mean lower energy densities; and most hardwoods grow slower and have higher energy densities. Softwoods are from gymnosperm trees, mostly evergreen species, e.g., pine, spruce, cypress, fir, hemlock, and redwood. Hardwoods are deciduous trees, e.g., poplar, willow, oak, cottonwood, and aspen. Wood residues, such as sawdust and barks from sawmills, wood chips, and branches from dead trees can also be used as lignocellulosic biomass feedstocks. Compared to agricultural biomass, which has to be collected at its ripe time, woody materials can be collected, transported and stored flexibly with time.

Similar to the forestry wood, fast-growing trees, such as willow, poplar, black locust, eucalyptus, chestnut, *etc.*, can also be used as biomass for power generation [12–19]. Fast-growing wood has been used to produce fuelwood, furniture materials, fiber for paper and cellulose industries, and also for bioenergy [20]. Fast-growing wood has many advantages, such as high yield in short time cycle, low cost of plantation and management, and possible opportunities for planting on non-agricultural lands. These fast growing trees have been planted in many countries, e.g., China, India, the United States, and some European countries. For example, poplar, black locust, eucalyptus, and willow were planted in different areas, depending on different climate and land options in Spain [15,21]. The plantation densities, the cultivation time periods, and the harvest of different fast wood crops are listed in Table 1. It obviously shows that the harvest mainly varies with different crop types and plantation densities.

Table 1. Summary of the plantation densities, the cultivation time periods and the harvest of different fast wood crops in Spain [15,21].

Crop	Plantation Density	Cultivation Period	Yield/Year
Eucalyptus	1428 plants ha^{-1}	15 years	5.2 t ha^{-1}·year^{-1}
Poplar	10,000 plants ha^{-1}	16 years	13.5 t ha^{-1}·year^{-1}
Black locust	1100 plants ha^{-1}	16 years	9 t ha^{-1}·year^{-1}
Willow	10,000 plants ha^{-1}	20 years	10 t ha^{-1}·year^{-1}

2.2. Feedstocks from Agricultural Crop Residues and the Cultivation

Agricultural crop residues are among the cheapest and most widespread lignocellulosic biomass resources. They are mostly from agricultural wastes, such as wheat straws, corn stover, rice straws, and husk, as well as non-food parts of other planted crops. Similar to the availability of forestry wood feedstocks, approximately 318–408 million tons of agricultural crop residues can be harvested per year in the United States [11]. They are mainly the residues from corn stover, rice, and wheat straws, and can be considered as the bioenergy feedstocks with the most potential in agricultural areas. Agricultural crop residues have a lower density than forestry wood and fast-growing wood, and are relatively expensive in collection and transportation. However, alternative use of agricultural residues can help us to avoid reliance on forestry wood and reduce deforestation. Another important aspect is that agricultural residues are the additional product of crop grain and can generally be harvested every year, so agricultural residues can be considered consistently available for bioethanol and power generation [22,23]. In contrast to forestry wood, the costs of the agricultural crop cultivation are critical. With regard to winter wheat cultivation in two European countries [24] as an example compared with corn plantation, Table 2 shows that the inputs and outputs vary according to differences in the climate and field conditions in the two countries. In the table, the yield straw is calculated on the ratio of grain and straw as 1:0.8.

Table 2. Main inputs and outputs of winter wheat cultivation compared with corn in Germany and Poland.

Parameter	Unit	Winter Wheat		Reference Source	Corn [24]
		Germany	Poland		
Yield grain	Kg·ha^{-1}	7430	3800	[25]	8000
Yield straw	Kg·ha^{-1}	5940	3040		6400
Diesel	Kg·ha^{-1}	75	75	[26]	160
Seeds	Kg·ha^{-1}	140	140	[26]	25
N-fertilizer	Kg·ha^{-1}	165	65	[26]	150
P-fertilizer	Kg·ha^{-1}	30	10	[26]	40
K-fertilizer	Kg·ha^{-1}	40	24	[27]	25
Herbicides	Kg·ha^{-1}	1.43	0.69	[27]	1
Insecticides	Kg·ha^{-1}	0.04	n.a.	[27]	2

2.3. Perennial Fast-Growing Grass and the Cultivation

Switch grass is perennial warm season bunchgrass that is native to the North American hemisphere, mainly in Canada and the United States [1,2]. Switch grass is not only a fast-growing grass, but also has some advantages, such as low cost compared to agricultural crops, wide distribution and abundance in the United States, and low maintenance, requiring little to no fertilization. Although typically shorter than big bluestem grass or Indian grass, switch grass can grow up to 2.7 meters high. Switch grass has another more attractive advantage of resistance to conditions of drought and high temperature because it uses C4 carbon fixation like corn. Because switch grass is perennial, self-seeding and has lifetime around 10 years or even longer, it does not need planting and reseeding after annual harvesting. However, in order to guarantee high yield every year, the necessary input and maintenance of the fast-growing grass are suggestive. Miscanthus giganteus is another perennial fast-growing grass that is a great candidate for power generation and biofuel production. It is native to Asia and has been planted in Europe for combustible energy use [28]. In Table 3, the inputs for cultivation and outputs from switch grass and miscanthus [24] are listed.

Table 3. The input of cultivation and output of switch grass and miscanthus [24].

Parameter	Units	Switch Grass	Miscanthus
Planting year			
N-fertilization	$kg \cdot ha^{-1}$	-	-
P-fertilization	$kg \cdot ha^{-1}$	87	87
K-fertilization	$kg\ ha^{-1}$	166	166
Seeds	$kg \cdot ha^{-1}$	5	5
Productive years			
N-fertilization	$kg \cdot ha^{-1}$	80	90
P-fertilization	$kg \cdot ha^{-1}$	8	8
K-fertilization	$kg \cdot ha^{-1}$	25	60
yield	$Mg \cdot ha^{-1}$	12	17

3. The Role of Transportation and Pelletization in the LCA

In contrast to renewable resources like wind, solar, and hydropower, the biomass feedstocks for electricity generation must be produced, collected, transported, and stored before their use in a power plant. The cost of biomass materials used in biomass power generation is critically dependent upon the availability of a secure long-term supply of biomass feedstock at a competitive price. The current worldwide cost of biomass feedstock can represent 40% to 50% of the total cost of electricity produced from biomass [29]. Considering the convenience, the lowest cost feedstock is agricultural residue, such as local wheat straw or rice straw, corn stover, and other agricultural residues, when they are collected at harvest. For forestry wood or residue, the collection and transportation costs are predominant. Comparing to coal and petroleum, the lower energy density of biomass feedstocks limits the transportation distance from a power plant, and farther transportation adds more feedstock costs in a power plant. Table 4 lists the typical costs of corn stover transportation, which are related to different equipment reported in the United States, and the data with farmer-owned equipment is calculated based on 810 ha (2000 acres) [30].

Bales of grass or agricultural residues and wood chips are convenient in the harvesting process, however, their low bulk and energy densities are the drawbacks for transportation [31,32]. Compared to the conventional forms of bales and chips from agricultural and forest biomass resources for power generation, pelletization of these resources is one major technology to save on transportation costs and to improve the efficiency of fuel conversion in the final process. Because of high density and low water content of pellets, pelletization reduces transportation cost and improves the conversion efficiency in power plants [31]. Pelletization also minimizes dust formation and helps the feed of free flow of biomass fuels because of the regular size of pellets.

Table 4. Transportation cost per ton with custom/owned equipment [30].

Transportation Distance	Cost with Custom Equipment	Cost with Farmer-Owned Equipment
8 km	$2.79	$3.33
16 km	$4.32	$4.07
24 km	$5.84	$4.81
32 km	$7.36	$5.55
40 km	$8.90	$6.28
48 km	$10.43	$7.02
56 km	$11.95	$7.76
64 km	$13.48	$8.50
72 km	$15.01	$9.24
80 km	$16.54	$9.98

4. The Role of Power Generation Methods in the LCA

There are three primary technologies applied for the biomass combustion in electricity factories, direct or dedicated burning and combined heat and power (CHP), co-firing with coal and gasification. The cost and efficiency of biomass power generation vary significantly by those three technologies. Equipment costs for each technology used in the power plants are also different, depending on the region, the nature of different feedstocks, feeding forms with bales, chips or pellets, and the scale of the power plants. Figures 1 and 2 show the inputs, different feedstocks, transportation, and different burning technologies in the pathways of power generation with/without pelletization.

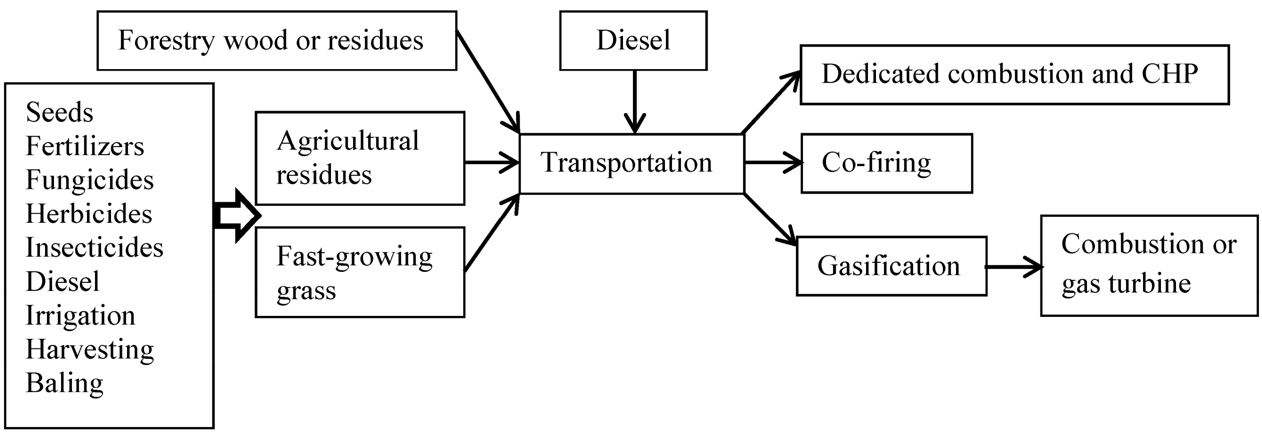

Figure 1. The power generation pathway from lignocellulosic biomass without pelletization.

Through combustion in dedicated power and CHP plants biomass can be used to produce electricity and CHP via a steam turbine. Direct combustion is the oldest and simplest, but most inefficient burning technology. The typical efficiency of direct combustion with biomass was 16.2%–20% in the 1990s [8], and it has been improved to 20%–22%, depending on the scale of biomass power plants, different feedstocks and feeding forms, e.g., bales, chips and pellets [33]. In CHP plants, the system of heat generation is parallel with electricity production, producing steam, hot water, or chilled water, optimally designed for the customer's needs and requirements of heating factories, green houses, *etc.* The total plant efficiency of CHP can reach 85%–90% [34]. The typical size of CHP plants is usually ten times smaller (from 1 to100 MW) than coal-based plants, depending on the availability of local feedstocks. Because of low sulfur content in lignocellulosic biomass, emission of pollutants from CHP plants can be effectively controlled compared to the coal-based plants.

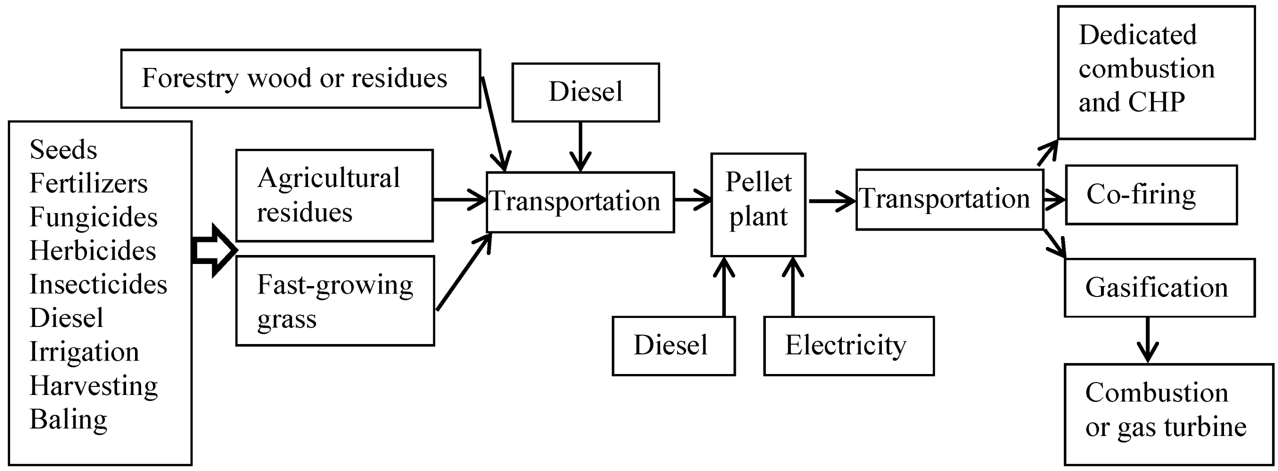

Figure 2. The power generation pathway from lignocellulosic biomass with pelletization.

With moderate additional investment, lignocellulosic biomass co-firing in modern, large-scale coal-based power plants can be more efficient and cost-effective. The co-firing technology has been applied in North Europe, the United States, Australia, and some Asian countries, using different feedstocks, such as forestry wood or residues, agricultural residues, and fast-growing crops [32,35–37]. The combustion efficiency of 35%–45% in large-scale plants is higher than that of biomass direct combustion plants, although it is lower than that in pure coal-based plants [38]. Generally, co-firing technology decreases the emissions compared to direct combustion, however, it depends on many factors [6], such as different biomass resources and coal characteristics, the coal utility boiler configuration and scale, *etc.*

In the gasification process, biomass conversion into syngas can be either from slow anaerobic fermentation or fast thermo-chemical processes, e.g., pyrolysis at elevated temperatures in the absence of oxygen and gasifying with common agents, such as air, oxygen, and/or steam [21,39]. Slow anaerobic fermentation converts only 50%–60% feedstock into biogas, but produces soil conditioners as a byproduct. Fast thermo-chemical processes produce much more biogas and even leave only 2%–4% of ash through pyrolysis. Currently, the biomass integrated gasification combined cycle is the most common approach for power generation from lignocellulosic biomass [40]. Gasification has higher efficiencies; however, it requires a significant investment and operations at elevated temperatures with extra energy consumption [41,42]. Compared to the previous two technologies, the emissions of burning biogas obtained from lignocellulosic biomass through gasification is the lowest.

5. GHG Emission Caused by Power Generation from Lignocellulosic Biomass

Most lignocellulosic biomass is composed of about 50% carbon, 40% oxygen, and 5% hydrogen by weight, as well as very small amounts of other elements. Burning biomass results in various emissions and most emissions are CO_2, H_2O with 0.3% NO_x and some CO and CH_4 using poorly-maintained equipment. In addition, the total emissions include some pollutants of 0.1% sulphur, 0.1% chlorine, and trace quantities of inorganic minerals, such as calcium, potassium, silicon, phosphorus, and sodium [26]. The compositions of emissions depend on many factors, including the growing environment of plants, the plant species, any contaminants in the soil, water, or air, *etc.* In most cases, power generation from lignocellulosic biomass produces low net carbon emissions, mostly in the form of CO_2, and 2% or less of total emissions of other GHGs, such as CH_4 and NO_x [43,44]. Burning biomass also avoids anaerobic decomposition that results in CH_4 emissions, which are known to have 21 times the greenhouse effects of CO_2. Generally power production from biomass is considered carbon neutral, with burning emissions balanced by the carbon capture of the next crop [45,46]. In some instances, with non-invasive farming methods, some researchers even claimed carbon negativity which means that less carbon is emitted than is removed from the atmosphere [47,48]. The GHG emissions from the combustions of biomass vary with biomass feedstocks, different forms, and power generation methods. Table 5 lists emission factors (emissions in kilogram per ton of biomass) for the combustion of biomass in different forms when only CO_2 emissions are considered carbon neutral [32,49,50] and other emissions are accounted for. GHG emissions of burning lignocellulosic biomass are generally, but not always, lower than the combustions of fossil fuel and coal. For example, using short rotation coppice chips or fast-growing trees in power plants can reduce 15% to 65% emissions than a combined cycle gas turbine power station, however, the emissions from using wheat straw, rice straw, or corn stover, reduces 35% emission savings. Transporting lignocellulosic biomass over long distances and excessive use of nitrogen fertilizers for short rotation coppice or switch grass further reduce the emissions savings by 15%–50% [51].

Table 5. Emission factors for of biomass combustion in different forms (units: kg/t) [32,49,50].

Emissions	Forestry Wood Pellet	Forestry Wood Chip	Agricultural Residue Pellet	Agricultural Residue Bale
CO_2	0	0	0	0
CH_4	0.00582	0.113	0.0046	0.0892
N_2O	0.0485	0.0699	0.0372	0.0536
CO	1.26	3.23	4.18	10.07
VOC	0.0291	0.0113	0.0291	0.0113
NO_x	1.44	1.38	1.67	1.60
SO_2	0.0485	0.134	0.839	2.31

The daily criteria pollutant emissions of power generation from different lignocellulosic biomass, such as forestry residue, miscanthus, willow, poplar, and switchgrass were evaluated through life cycle assessment by using GREET.net 2014 (The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation Model, 2014 version) [52]. The capacity of the different power plants is 1 MW, which falls in a small plant scale. The mode of well-to-pump was used in the simulation. Table 6 shows the characteristics of farming inputs and different emissions of electricity generation with different lignocellulosic feedstocks in the USA in 2014. The unit kg/t refers to the usage of fertilizers or herbicides in kg for a 1 ton output of dry biomass in the pathway. Here, the same transportation distance of 50 miles is used for all the biomass types. We can see that the pollutant emissions of VOC, CO, NOx, PM10 and PM2.5, and the GHG emissions are similar for all the feedstocks. The SO_x emissions vary with different feedstocks: the emission from burning forestry residue is the greatest, and those from Poplar are the smallest. The N_2O emissions also vary with different feedstocks and the emissions from switchgrass are the greatest. The daily net emissions of the GHGs (CO_2-equivalent) for all the different feedstocks are much lower than those at on-site power plants. The lowest GHG emissions are achieved with the willow feedstock.

Table 6. The characteristics of farming inputs and daily emissions of electricity generation with different lignocellulosic feedstocks.

Farming	Unit	Forest Residue	Miscanthus	Willow	Poplar	Switchgrass
N-fertilizer	kg/t	N/A	4.407	0.436	3.014	9.147
P-fertilizer	kg/t	N/A	1.539	N/A	1.008	0.125
K-fertilizer	kg/t	N/A	6.275	N/A	2.015	0.251
Herbicides	kg/t	N/A	0.035	0.005	0.150	0.035
Calcium carbonate	kg/t	N/A	N/A	N/A	2.380	N/A
VOC	kg	3.722	4.5336	4.120	4.279	5.102
CO	kg	116.194	117.130	116.638	117.250	117.900
NO_x	kg	27.295	29.894	28.942	29.964	32.323
PM10	kg	67.908	68.191	68.006	68.162	68.290
PM2.5	kg	47.755	47.976	47.837	47.964	48.065
SO_x	g	232.855	40.807	23.340	2.825	55.872
CH_4	kg	13.075	14.728	13.735	14.138	15.319
N_2O	kg	1.582	4.574	3.418	3.384	7.922
CO_2	kg	49,121.520	39,718.480	40,165.730	40,178.184	41,554.522
GHGs	kg	6507.813	3110.010	2461.972	2746.449	4355.243

6. Uncertainty Analysis of Electricity Generation from Lignocellulosic Biomass

The emission analysis described herein is limited to parameters for which data were readily available in GREET.net 2014. Within the LCA, differences in agricultural chemical usage and transportation distances usually vary between scenarios. This analysis does not consider the environmental impacts driven by land-use change, either direct or indirect, or impacts resulting from establishing new infrastructure for power plants. However, increasing demand for power generation from lignocellulosic biomass may significantly change land use patterns and stimulate infrastructure construction. The emission factors of each pathway should be determined with the characteristics of different feedstocks, the details of different technologies of power generations and the power plant scales. For examples for CHP power generation, the emission factors rely on the details of the boilers installed and the plant scales. The achievement of power-generation increases from biomass depends on biomass power plant capacity and regional feedstock resources. In the sensitivity study of the above-mentioned case, the results show the power generation efficiency obviously affects the pollutant emissions. In detail, there exists about a 4.8% or 7.4% increase when the power generation efficiency decreases by 1% or 1.5% from the base of 21.9%, which is applied in the GREET.net 2014; however, the emissions are reduced by about 4.4% or 6.4% when the efficiency increases by 1% or 1.5%.

7. Conclusions

The energy crisis and reduction of GHG are critical issues that have to be solved. Renewable biomass, especially lignocellulosic biomass, is abundant and complementary to non-renewable fossil resources. Many technologies are developed to derive biodiesel, bioethanol, or generate electricity from non-food biomass. Currently, the derivation technologies of biofuel from biomass are not mature, although they have started in some pioneer plants. Biomass combustion is relatively easy and is widely applied in many countries. Many case studies illustrated that LCA is effective to quantify the environmental impacts of power generation from biomass. LCA includes all the stages, from cradle-to-grave, along the whole process, from planting or collecting lignocellulosic biomass to electricity generation in biomass-only based or co-firing plants.

The evaluations of lignocellulosic biomass for power generation are complicated with different options in LCA. The analysis results of LCA vary with different feedstocks, feedstock transportation, burning technologies applied to different plant scales, and GHG emissions. Although power generation from lignocellulosic biomass is a general carbon neutralization process, the overall carbon footprint depends on many factors, such as different inputs related to different feedstocks, feedstock transportation, and the methods of electricity production. Due to low energy density, the transportation cost of lignocellulosic biomass is more sensitive to economic efficiency of power plant location and scales of power plants shown in some LCA studies. LCA has also been used to quantify the GHG emission savings of power generation from biomass by comparing the emissions with a reference energy generation system from coal, fossil fuel, or natural gas. Overall, 7.5% to 65% savings can be achieved with different feedstocks, such as agricultural residues, grass, and wood. The results of the case study, fed with different lignocellulosic biomass, such as forestry residue, miscanthus, willow, poplar, and switchgrass, show that the lowest GHG reductions were achieved at the willow power plant.

Compared to power generation from coal or fossil fuels, the economic efficiency of lignocellulosic biomass is generally lower. The total cost of power generation, based on lignocellulosic biomass, varies with the inputs of feedstocks, transportation distance, and the costs on power plants. Direct burning as a mature technology is globally used, and some other methods are being demonstrated and developed. In the short term, the barriers to widely use biomass for power generation are cost, low conversion efficiency, and feedstock availability. In the long term, the future of bio-power generation will depend on the urgency of greenhouse effects and energy crisis, advanced technology development of feedstock cultivation, and efficient burning methods, carbon capture, and storage, as well as the competition with the conversion efficiency of biomass into biofuel, such as bioethanol or biodiesel.

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Author Contributions

Xinhua Shen primarily worked on the project and prepared the initial draft of the manuscript under the guidance of Raghava R. Kommalapati. Ziaul Huque is a collaborator on the project. Both Kommalapati and Huque contributed in revising and preparing the final draft of the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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