Hindawi Publishing Corporation
International Journal of Chemical Engineering
Volume 2013, Article ID 492058, 16 pages
http://dx.doi.org/10.1155/2013/492058

Research Article

Life Cycle Costs and Life Cycle Assessment for the Harvesting, Conversion, and the Use of Switchgrass to Produce Electricity

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Received 2 May 2013; Revised 16 July 2013; Accepted 21 July 2013

Academic Editor: Antonia Pérez de los Ríos

This paper considers both LCA and LCC of the pyrolysis of switchgrass to use as an energy source in a conventional power plant. The process consists of cultivation, harvesting, transportation, storage, pyrolysis, transportation, and power generation. Here pyrolysis oil is converted to electric power through cocombustion in conventional fossil fuel power plants. Several scenarios are conducted to determine the effect of selected design variables on the production of pyrolysis oil and type of conventional power plants. The set of design variables consist of land fraction, land shape, the distance needed to transport switchgrass to the pyrolysis plant, the distance needed to transport pyrolysis oil to electric generation plant, and the pyrolysis plant capacity. Using an average agriculture land fraction of the United States at 0.4, the estimated cost of electricity from pyrolysis of 5000 tons of switchgrass is the lowest at \$0.12 per kwh. Using natural gas turbine power plant for electricity generation, the price of electricity can go as low as 7.70 cent/kwh. The main advantage in using a pyrolysis plant is the negative GHG emission from the process which can define that the process is environmentally friendly.

1. Introduction

Our dependence on fossil fuel has increased over the past century due to increasing energy consumption. The U.S. Department of Energy [1] stated that transportation energy demand is increasing at an annual rate of 0.2 percent from year 2010 to 2035. Total electricity consumption is also increasing at an annual rate of 0.8 percent from 3879 billion kilowatt-hours in 2010 to 4775 billion kilowatt-hours in 2035. On the other hand, the world oil reservoir is decreasing. From BP's estimates [2], world oil production has already reached its maximum and is expected to drop. At the present production rate, the world oil reservoir will last for forty-one years. Renewable energy such as biooil will be an alternative source to make up the reduction of oil production rate. Faaij [3] reported that fossil fuel dominated the world's energy uses, supplying 80% of the total energy requirement. However, 10–15% of this demand could be covered by biomass resource. Biomass is an important energy resource for developing countries accounting for 50–90% of their total energy requirement. Advantages of biomass energy include potential to reduce GHG emissions, substitution for depleting global crude oil reservoir, potential impacts on waste management, and the conversion of waste resources into clean energy. Waste resources include natural forests wood, forestry residues, agricultural residues, industrial wastes, food processing wastes, and municipal solid wastes.

With the increasing concern of greenhouse gas from petroleum sources, searching for clean and environmental friendly energy resource has become more important [4]. Richard et al. [5] reported perturbation of greenhouse gas such as carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O), which have been created by human activity such as utilization of fossil fuel and landuse change to the global climate. A measurement of carbon dioxide at Mauna Loa Observatory showed that the rate of release of carbon dioxide into the atmosphere has increased from less than 1 ppm per year in 1970 to more than 2 ppm per year in 2009. It is expected that the rate will increase exponentially [6].

Biooil is one of the promising clean energy substitutes since it can be replaced or mixed with fossil fuel to use in a conventional technology engine. In this study, the biooil is produced and used in conventional power plant. Hammons [7] reported a study of greenhouse gas emissions from electric power plant in Europe. Carbon dioxide from fossil fuel combustion in a power plant is more than one-third of the total carbon dioxide emission and the fraction is increasing. From AEO 2012 [8], carbon dioxide produced from electricity generation is increasing at a rate of 0.2 percent per year until 4.9 percent from year 2010 to 2035. Brammer et al. [9] reported on the use of biooil in heat, power, or combined heat and power (CHP) in 14 European countries. They reported that heat application is the most economically competitive followed by CHP application. Fan et al. [10] conducted life cycle assessment of electricity generation using fast pyrolysis biooil from short rotation forestry willow, poplar, collection of hard wood residue from existing forestry operations, and wasted wood from a sawmill available at the site of pyrolysis plant. They reported that using fast pyrolysis oil in power plants could save GHG emission about 77%–99% depending on the biomass feedstock and type of power plant. Solantausta et al. [11] reported the use of fast pyrolysis oil in diesel engine in power plant. The modification in diesel engine by adding injection system which help ignition of the fuel consistence is necessary. Arbon [12] reported on the use of biomass in power generation. He discussed the use of pyrolysis and gasification product in conventional combustion system such as steam turbine, boiler, and reciprocating engine. However, the development in technology is needed to reduce high capital cost of pyrolysis process. Chiaramonti et al. [13] reported on the use of pyrolysis in diesel engine, gas turbine, and natural gas/steam power plant.

Advantages of using fast pyrolysis oil as fuel are that it is easy to store and transport; it has a higher energy density than gasification fuel gases; it can be distilled and replaced by light fuel oil, and it can be used in conventional fossil fuel power plant [13]. Arbogast et al. [14] reported the economic study of pyrolysis oil. The authors concluded that waste biomass such as logging residues is the lowest cost material for pyrolysis oil. However, there is a supply limitation for waste biomass material. On the other hand, growing energy crop is more expensive. However, with more concentrated production of energy crop, logistic cost can be reduced. Growing energy crop provides a more stable energy source thus reducing the limitation of pyrolysis oil production. Boateng et al. [15] stated that pyrolysis oil from switchgrass as an energy crop has a yield greater than 60%. The energy conversion efficiencies of switchgrass are ranked between 52% and 81%. This paper focuses on life cycle assessment and life cycle cost of using switchgrass as an energy crop from field to power plant.

The rest of the paper is organized as follows. Section 2 is the background for LCA (life cycle assessment), LCC (life cycle cost), and switchgrass. Section 3 describes the methodology in this work. Section 4 presents and discusses the results. The final section is the set of conclusions for this work.

Table 1: Biomass yield of switchgrass cultivars grown in southern Iowa from 1998 to 2001 [21].

Varieties	Yield ($Mg\,ha^{-1}$)
Upland	
Trailblazer	7.9
Blackwell	8.3
Cave-in-Rock	9.3
Pathfinder	7.3
Caddo	7.8
Lowland	
Alamo	12.1
Kanlow	13.1

2. Background

2.1. Switchgrass. Switchgrass (*Panicum virgatum* L.) is a perennial grass native to Central and North America. It is a promising bioenergy source for the following reasons: long life (more than 10 years), high productivity, adaptability, and high potential of integration into conventional agricultural operation. There is a significant opportunity for using switchgrass in ethanol production and also combustion fuel source for power production due to its high cellulosic content. Switchgrass can be grown in many different regions including marginal land areas due to its highly adaptability and persistence. Moreover switchgrass is tolerant to cold weather and disease [16–19].

There are many environmental benefits from growing switchgrass such as increasing soil quality, reduced losses of soil nutrients, and recycling nutrients from municipal and agricultural wastes, soil carbon sequestration, and mitigating greenhouse gas emissions. There are 14 million ha of Conservation Reserve Program (CRP) lands, which were created by the USA Food Security Act of 1985, in order to remove land from crop production and place a long-term resource-conserving vegetation cover to prevent soil erosion, improve water quality, and enhance wildlife habitat. These lands have the potential to be used as areas for biomass production [19, 20].

Switchgrass can be separated into two categories, namely, upland and lowland types. The upland types are suited to drier soils and are better in semiarid climates. On the other hand, the lowland types grow better in heavier soils and require more water. However, the lowland types have a higher dry mass production than the upland type. The upland types include Trailblazer, Blackwell, Cave-in-Rock, Pathfinder, and Caddo. Alamo and Kanlow are the lowland types [16].

Table 1 shows the yield of several switchgrass cultivars grown in southern Iowa. Lemus et al. [21] state that the mean yield of 20 switchgrass cultivars grown in southern Iowa and harvested in autumn 1998 through 2001 was 9.0 $Mg\,ha^{-1}$. Fike et al. [22] reported that because of the lowland switchgrass greater productivity, they appeared better suited to biomass production in the upper southeastern USA. For the upland switchgrass, two cuts per year may be benefit dependent on production cost and feed stock quality. On the other hand, for the lowland switchgrass, two harvests per year may be less advantage for the biomass yield.

2.2. LCA. The international scientific society of environmental chemists (SETAC) [23] defines LCA as "a process to evaluate the environmental burdens associated with a product, process, or activity by identifying and quantifying energy and materials used and wastes released to the environment." The LCA frame work was developed by the International Organization for Standardization in ISO14000 series: ISO14000 on principle and frame work, ISO14041 on goal and scope definition and inventory analysis, ISO14042 on life cycle impact assessment, and ISO14043 on life cycle interpretation [24]. LCA focuses only on the environmental impacts from the production system; that is, economic and social aspects are not considered [25]. LCA of biomass in this case is applied to switchgrass: from cradle which is the cultivation of switchgrass to grave, which is electricity from power plant.

2.3. LCC. Renewable energy in the form of biooil from pyrolysis of biomass (such as switchgrass) can only exist without government subsidies when the production cost is lower or equal to that of fossil fuel energy. Therefore, in this work, a total economic analysis is necessary in order to evaluate the economic viability. Ravemark [26] defines LCC as the sum of costs (present values of investment, capital, installation, energy, operating, maintenance, and disposal) over the life-time of the project, product, or measure. Barringer [27] indicated that life cycle costs (LCC) were cradle to grave costs summarized as an economics model of evaluating alternatives for equipment and projects. Kawauchi and Rausand [28] stated that the main purpose of doing life cycle cost analysis was to find the total cost of production throughout its life cycle, which included research and development, construction, operation and maintenance, and disposal. LCC assesses the ability of using the switchgrass in pyrolysis process to create an alternative energy source which will finally be used in power plant to create electricity.

3. Methodology

In this work, we study LCC and LCA for the harvesting, conversion, and the use of switchgrass to produce electricity. The model system is defined in Figure 1.

In Figure 1, the process begins with the cultivation and harvesting in switchgrass farming. Subsequently, all the switchgrass is transported to storage. In the next step, switchgrass is transported to the pyrolysis plant to be converted to pyrolysis oil. Next, the pyrolysis oil is transported to the power plant for electricity generation. In this work zero net carbon emission is assumed. All of the GHG emission created at this stage is adsorbed and used in the photosynthesis of switchgrass in switchgrass field.

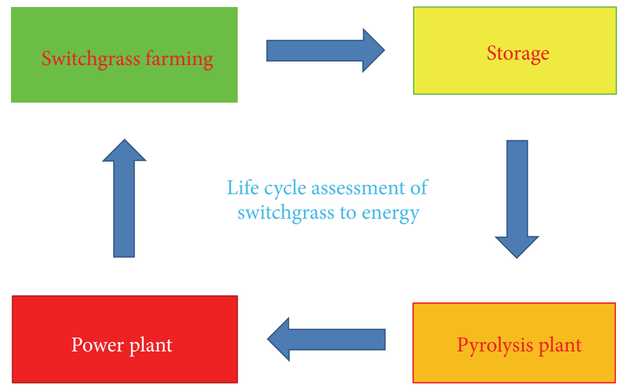

Figure 1: Life cycle assessment of switchgrass to energy.

LCA Model. Mass balances are employed as follows.

(1) Total emission for LCA model = (total emission from switchgrass field) + (total emission from transportation of switchgrass) + (total emission from storage process) + (total emission from pyrolysis plant) + (total emission from transport pyrolysis oil) + (total emission from power plant).

(2) Total emission from switchgrass field = (total emission from fuel used in the field) + (total emission from fertilizer and herbicide).

(3) Total emission from transportation of switchgrass = (total emission of fuel used in transportation).

(4) Total emission from storage process = (total emission of fuel used in the storage system) + (total emission from the mass loss during keeping).

(5) Total emission from transportation of pyrolysis oil = (total emission of fuel used in transportation).

LCC Model. The total cost of the whole process is broken down as follows.

(6) Total cost for LCC model = (total cost from switchgrass field) + (total cost of transportation of switchgrass) + (total cost from storage + total cost from pyrolysis process) + (total cost from transportation of pyrolysis oil) + (total cost from power plant).

(7) Total cost from switchgrass field = (total cost of machinery) + (total cost of fuel) + (total cost of fertilizer and herbicide) + (loan interest).

(8) Total cost of transportation of switchgrass = (total cost of fuel and labor).

(9) Total cost from storage = (total cost of construction of storage) + (total cost of fuel and labor) + (total cost of switchgrass lost during storage).

(10) Total cost from pyrolysis process = (total cost of establishing pyrolysis plant) + (operating cost) + (switchgrass cost) + (maintenance cost) + (loan interest).

(11) Total cost of transportation of pyrolysis oil = (total fuel cost and labor).

(12) Total cost from power plant = (capital cost) + (operation cost) + (maintenance cost).

We employed a Dell computer workstation with Intel(R) Xeon(R) CPU E5405 2.00 GHz and the Matlab software environment [29] to perform the calculations.

3.1. Cost of Establishing, Reseeding, and Producing Switchgrass. Table 2 shows the estimated costs of establishing the switchgrass and GHG while Table 3 shows the estimated reseeding costs per ha and GHG. Table 4 shows the estimated yearly production costs per ha and GHG.

3.2. Biomass Transportation. In this work, we assumed that switchgrass was collected from the field to the pyrolysis plant located in the center of the circle with radius R_{circle}. Overend [37] developed a model to compute the transportation distance between the point of harvesting biomass and the central processing plant:

(13) $R_{circle} = 0.6833\tau\sqrt{n/\phi}\sqrt{P/M}$.

τ is the tortuosity factor of the road; this is a function of the terrain and can range from 1.27 where a regular rectangular road grid is superimposed over a flat terrain to in excess of 3 for a complex or hilly terrain constrained by geographical features such as lakes and swamps. n is the number of sectors to complete a circle. ϕ is the fraction of terrain devoted to switchgrass. P is the pyrolysis plant scale in ton/day. M is the switchgrass productivity in ton/(ha∗year). It is assumed that switchgrass is transported by 20 tons semitrucks:

$$A = \frac{P \times 330\ \text{days}}{M\phi}\ (\text{ha}). \qquad (1)$$

A is the area of switchgrass field in ha units. The switchgrass is assumed to be grown by farmers around the pyrolysis plant.

In Figure 2, switchgrass is grown in different farms in the upper right quadrant. The number of sectors to complete a circle is four since the circle was separated into four pieces. The fraction of terrain devoted to switchgrass is total area of every farm per area of the upper right quadrant. The red line is the road between a farm and a pyrolysis plant.

We assume that 20 tons of switchgrass is transported per truck. The truck mileage is assumed to be 2.4 km/L [38]. The driver cost is assumed to be \$0.6/mile (\$0.38/km). We assume that 4% of switchgrass is lost during transportation.

In Figure 3, emission from transportation of switchgrass to storage depends on the distance from the field to storage and that means emission per ton of switchgrass increases as the plant capacity increases.

3.3. Land Use Change Effect. There are many studies reported on the carbon deposit into a soil after growing switchgrass. Planting switchgrass can increase the carbon deposit rate into 0.2–1.1 tC/(ha∗a) [39]. The carbon dioxide was reported to be sequestered into the soil 1.79 tons of carbon dioxide per acre per year [40]. However, with the wide range of carbon deposit

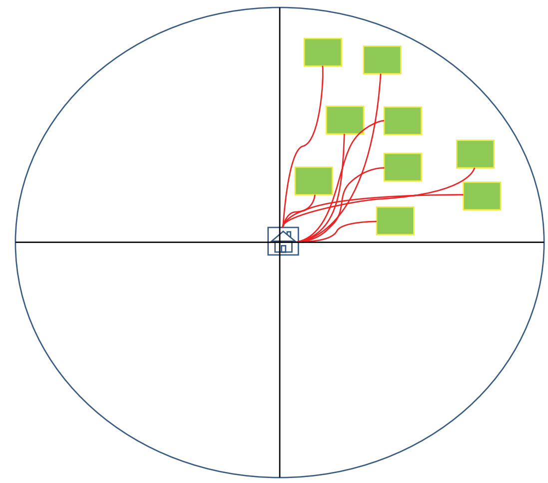

Figure 2: Calculating harvesting distance from farm to central pyrolysis plant.

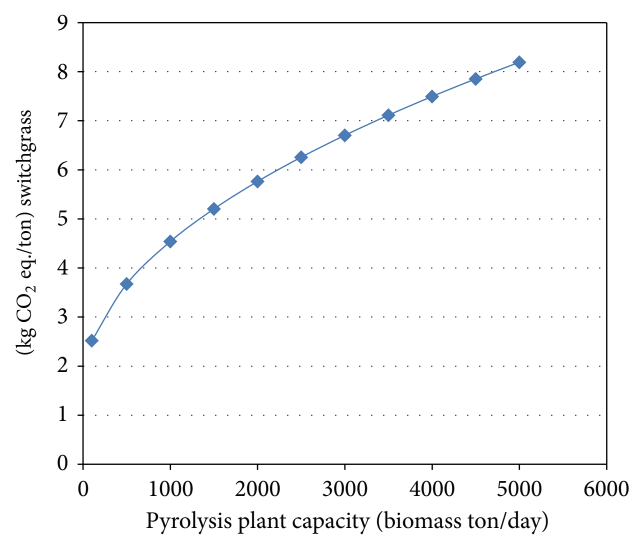

Figure 3: Dependence of emission from switchgrass transportation on pyrolysis plant capacity.

rate reported, the calculation is complex. The assumption is necessary. Cherubini and Jungmeier [41] gave an assumption of a C sequestration rate of 0.6 tC/(ha∗a). In this work, the value of soil organic compound at 0.49 ton/acre/year is assumed for the first two years of establishment case and 1.5 ton/acre/year is assumed for mature crop case [42].

3.4. Storage. Table 5 shows initial construction costs of the selected storage systems (storage losses are not included). From Table 6, the pole frame structure-enclosed on crushed rock (used in our work) loses the least amount of switchgrass compared with other storage types. We assume that the labor cost is \$12/hour. The tractor cost is \$20/hour. The unload time and storage time for one truck are half hour. The unload time from storage is 20 min. Emission from the storage process is 0.92 kg CO_2 eq. per ton of switchgrass.

Table 2: The estimated costs of establishing switchgrass and GHG [30–34].

The switchgrass							
Preharvest machinery operations custom charges	$/ha	Diesel (gal/ha)	Diesel cost $/ha	CO_2 (kg)	N_2O	CH_4	Estimate CO_2 equivalent/ha
Disk	31.01	3.46 (13.10 L/ha)	12.97	37.10	0.0152	0.0020	41.85
Harrow	19.10	1.24 (4.69 L/ha)	4.63	13.25	0.0054	0.0007	14.95
Airflow spreader (seed and fertilizers)	31.26	1.48 (5.60 L/ha)	5.56	15.90	0.0065	0.0009	17.93
Spraying chemicals	8.28	0.49 (1.85 L/ha)	1.85	5.30	0.0022	0.0003	5.98
Total	**89.65**	**6.67 (25.25 L/ha)**	**25.02**	**71.56**	**0.0292**	**0.0039**	**80.70**
Operating expense	Price $/unit	Unit/ha	$/ha				
Seed	$7.5/lb ($16.5/kg)	14.83 lb (6.74 kg)	111.20				
Fertilizer*							
N	$0.31/lb ($0.68/kg)	264.55 lb (120.25 kg)	82.01		5.05	1.20	1590.94
P	$0.37/lb ($0.81/kg)	74.13 lb (33.70 kg)	27.43				
K	$0.23/lb ($0.51/kg)	98.84 lb (44.93 kg)	22.73				
Lime	$21/ton	7.41 ton	155.68				
Herbicides**							79.8
Pursuit +	$53/gal ($14.00/L)	7.41 oz (0.22 L)	3.06				
MSO	$1.75/pt ($3.70/L)	79.07 oz (2.34 L)	8.65				
2,4D	$16/gal ($4.23/L)	3.71 pts (1.76 L)	7.41				
Total operating costs	418.17 $/ha						
Total establishment (11 years at 8% amortization (.14008 factor))	532.84 $/ha						
Prorated yearly establishment cost per ha	72.99 $/ha						

*The application of nitrogen fertilizer leads to the formation of nitrous oxide emissions from the soil which leads to emission of GHG.
**The emission of GHG from application of herbicide on a field.

Table 3: The estimated reseeding costs per hectare and GHG [30–34].

Reseeding probability 25%							
Preharvest machinery operations custom charges	$/ha	gal of diesel/ha	diesel cost/ha	CO_2	N_2O	CH_4	Estimate CO_2 equivalent/ha
Airflow spreader (seed and fertilizer)	31.26	1.48 (0.70 L/ha)	5.56	15.90	0.0065	0.00087	17.93
Spraying chemicals	8.28	0.49 (0.23 L/ha)	1.85	5.30	0.0022	0.00029	5.98
Total	**39.54**	**1.97 (0.93 L/ha)**	**7.41**	**21.20**	**0.0087**	**0.00116**	**23.91**
Operating exp. Price/unit Units	Price/unit	Unit/ha	$/ha				
Seed	$7.5/lb ($16.5/kg)	3.71 lb (1.69 kg)	27.80				
Fertilizer*							
N	$0.31/lb ($0.68/kg)	264.55 lb (120 kg)	82.01		5.05	1.20	1590.94
P	$0.37/lb ($0.81/kg)	74.13 lb (32.62 kg)	27.43				
K	$0.23/lb ($0.51/kg)	98.84 lb (44.83 kg)	22.73				
Herbicides**							79.8
Pursuit +	$53/gal ($14.00/L)	7.41 oz (0.22 L)	3.06				
MSO	$1.75/pt ($3.70/L)	79.07 oz (2.34 L)	8.65				
2,4D	$16/gal ($4.23/L)	3.71 pts (1.76 L)	7.41				
Total operating costs	179.09 $/ha						
Total reseeding costs (10 years at 8% amortization (.14903 factor))	226.04 $/ha						
Prorated yearly reseed cost per ha	32.91 $/ha						

*The application of nitrogen fertilizer leads to the formation of nitrous oxide emissions from the soil which leads to emission of GHG.
**The emission of GHG from application of herbicide on a field.

Table 4: The estimated yearly production costs per hectare and GHG [30–34].

Estimated yearly production costs							
Expected yield per ha	9 tons						
Weight of large square bale	950 lbs	431.82 kg					
Bales per ha	20.84						
Pre-harvest machinery operations custom charges	$/ha	gal of diesel/ha	diesel cost/ha	CO_2	N_2O	CH_4	Estimate CO_2 equivalent/ha
Bulk fertilizer spreader	8.28	0.49 (1.85 L/ha)	1.85	5.30	0.0022	0.00029	5.978
Liquid N application and sprayer	17.42	1.48 (5.60 L/ha)	5.56	15.90	0.0065	0.00087	17.93
Total	**25.70**	**1.97 (7.46 L/ha)**	**7.41**	**21.20**	**0.0087**	**0.00116**	**23.91**
Operating Exp. Price/unit Units	Price $/unit	Unit/ha	$/ha				
Fertilizer*							
N	$0.31/lb ($0.68/kg)	247.11 lb (112.09 kg)	76.60		4.72	1.12	1486.00
P	$0.37/lb ($0.81/kg)	4.79 lb (2.17 kg)	1.77				
K	$0.23/lb ($0.51/kg)	56.34 lb (25.56 kg)	12.96				
Herbicides**							79.8
Pursuit +	$53/gal ($14.00/L)	7.41 oz (0.22 L)	3.06				
MSO	$1.75/pt ($3.70/L)	79.07 oz (2.34 L)	8.65				
2,4D	$16/gal ($4.23/L)	3.71 pts (1.76 L)	7.41				
Total operation cost							
Harvest machinery operations, custom charges	Cost without fuel ($/ha)	gal of diesel/ha	diesel cost/ha				
Mow/conditioning	36.37	2.792 (10.57 L/ha)	10.47	29.95	0.012	0.0016	33.76
Rake	13.81	0.766 (2.90 L/ha)	2.87	8.216	0.003	0.0004	9.27
Baling: large square	45.22	2.644 (10.01 L/ha)	9.92	28.36	0.012	0.0015	31.98
Staging	49.42	2.471 (9.35 L/ha)	9.27	26.50	0.011	0.0014	29.89
Total	**144.83**	**8.67 (32.82 L/ha)**	**32.53**	**114.2**	**4.764**	**1.1294**	**1694.63**
Yearly production costs per ha	320.92 $/ha						
Prorated establishment cost	72.99						
Prorated reseeding cost	32.91						
Total production costs	**426.82**						
Production costs per ton	47.42						

*The application of nitrogen fertilizer leads to the formation of nitrous oxide emissions from the soil which leads to emission of GHG.
**The emission of GHG from application of herbicide on a field.

Table 5: Initial construction costs of the selected storage systems (storage losses are not included) [35].

Storage system for square bales (950 lb/bale)	Cost per m^2 ($)	Life years	Annual costs ($/$m^2$)	Cost per bale ($)		Cost per ton ($)	
Collective storage facility	107.64	15	12.58	10 bales high 3.77		10 bales high 7.95	
Pole frame structure-enclosed on crushed rock	70.39–107.64	15	8.22–12.58	5 bales high 4.93–7.55	6 bales high 4.11–6.29	5 bales high 10.39–15.89	6 bales high 8.66–13.24
Reusable tarp on crushed rock (19.8 sq. ft/bale i.e., 1.84 m^2/bale)	1.47	5	0.37	4 bales high 1.39		4 bales high 2.92	
Outside Unprotected on crushed rock	2.70	5	0.68	0.51		1.07	
Outside and unprotected on ground	0.00	—	0.00	0.00		0.00	

Table 6: Storage systems and expected dry matter loss [35].

Storage system for square bales (950 lb/bale)	Average DM loss (%)
Pole frame structure-enclosed on crushed rock	2
Pole frame structure-open sides on crushed rock	4
Reusable tarp on crushed rock	7
Outside Unprotected on crushed rock	15
Outside and unprotected on ground	25

Table 7: Biorefinery capital cost components based on the reference plant size [36].

Capital cost	
Fast pyrolysis (28 mmgpy bio-oil)	Cost (millions)
Handling and drying	5.57
Pyrolysis reactor	3.92
Quench	1.94
Heat recovery	1.14
Product recovery and storage	0.8
Recycle	1.38
Steam and power production	3.16
Utilities	3.13
Contingency	7.37
Total	28.41

3.5. Pyrolysis Oil Production. In this paper we have chosen pyrolysis for producing biooil. Boateng et al. [15] designed a bench-scale pyrolysis reactor to convert switchgrass to biooil. We assumed a pyrolysis plant based on the authors' work. Results from the authors show that switchgrass pyrolysis could yield over 85% of mass basis. The product consists of biooil 60.7%, biochar 11.3%, and noncondensable gas 12.9% in mass basis. The noncondensable gas consists of CO_2 29%, CO 57.6%, H_2 5.1%, and CH_4 7.8% by volume. In this work, the biooil product is assumed to be 60.7% wt as the lowest yield for switchgrass that author suggested. The pyrolysis oil is assumed to be transported by a tank truck capacity of 11600 US gallons. The mileage of the tank truck is 2.4 km/L [38]. Emission from the storage process is $6.2 * 10^{-3}$ kg CO_2 eq. per ton of switchgrass.

Table 7 shows the biorefinery capital cost while Table 8 shows the operating cost for the plant. Table 9 shows production from pyrolysis of switchgrass. Properties of pyrolysis oil are shown in Table 10.

3.6. Power Generation. Power generation from fossil fuels is one of the major greenhouse gas producers, an estimated one-third of the carbon dioxide emissions in Europe. The pyrolysis oil can be used as a substitute of fossil fuels in conventional power plants such as gas engines, gas turbines, and coal fired plants in order to reduce greenhouse gas emissions. Pyrolysis oil is acidic, unstable, contains solid residue, and many chemicals in biooil dissolve in water. The heating value, density, and viscosity of biooil depend on water and additives in the biooil, which also differs from fossil fuels. These factors are problematic in using pyrolysis oil in conventional power plants. Despite these problems, biooil still can be used in the conventional power plants by modifying the engines as many studies suggest [7, 13]. Balat et al. [48] also suggested the main route of using the biooil in boilers, diesel engines, or gas turbines for heat and electricity generation. In this work, the power plant is assumed to operate 8760 hour/year. The main power technologies considered in this work are discussed below.

Table 8: Biomass fast pyrolysis annual operating cost components based on the reference plant size [36].

Fast pyrolysis operation cost	Cost	Explanation
Water treatment	1	Linear scaling
Electricity	0.21	Linear scaling
Labor	1.34	0.6 power law scaling
Overhead	0.8	60% labor
Maintenance	0.57	2% equip
Insurance/taxes	0.72	1.5% TCI
Charcoal (credit)	1.92	50/ton

Table 9: Production from pyrolysis of switchgrass [15].

Product	% wt
Biooil	60.7%
Biochar	11.3%
Noncondensable gas	12.9%

Table 10: Properties of pyrolysis oil [15].

Property	
Density at 15°C, kg/L	1.25
Kinematic viscosity at 50°C, cSt	13.11
Kinematic viscosity at 100°C, cSt	2.54
Heat of combustion, MJ/kg	16.02
Ash at 775°C, wt%	0.01

Table 11: Power plant efficiency.

Power plant	Efficiency	Reference
Diesel engine	32.4%	[13]
Gas turbines	42%	[43]
Steam turbine coal-fired power plant	33%	[43]
Steam turbine fuel-oil power plant	34%	[44]

Table 11 shows power plants efficiency. Table 12 shows specification on wt% of pyrolysis liquid component (to be able to use as fuel in boilers, engines and turbines). Comparing specification pyrolysis oil from Oasmaa et al. with pyrolysis oil from switchgrass, we assume that the pyrolysis oil from switchgrass can be used in boilers, engines, and turbines.

3.6.1. Diesel Engine Power Plant. Yoshikawa [49] studied the efficiency of the diesel engine in power plants when using low-BTU fuel gas which was produced by pyrolized solid fuel.

Table 12: Specification on wt% of pyrolysis liquid component (to be able to use as fuel in boilers, engines, and turbines) [45].

Component	Specification to be met	Pyrolysis oil from reference switchgrass [15]
Water	<27 wt%	23 wt%
Total solids	<0.01 wt%	0.01 wt%*
Inorganics	<0.01 wt%	0.01 wt%*

*Ash content.

The result showed that the efficiency of diesel engines was about 30%. Solantausta et al. [50] reported the efficiency of 34% using pyrolysis oil in diesel. In this paper, the thermal efficiency of diesel engines which use pyrolysis oil is assumed to be 32.4% [13].

3.6.2. Pyrolysis Oil Substituting Natural Gas in Gas Turbines. In order to use pyrolysis oil in gas turbines, the gas turbine engine must be modified and pyrolysis oil needs to be upgraded. The gas turbine engine must be able to resist low pH substance which is pyrolysis oil. The nozzles must be modified for higher flow cause by lower heating value and higher viscosity of pyrolysis oil. The preheating unit to heat the pyrolysis oil to 70–90°C is necessary to reduce the viscosity of pyrolysis oil to less than 10 cSt [13]. However, Wagenaar et al. [51] reported the use of biooil to substitute the natural gas in the real power plant. The experiment showed the possibility of using pyrolysis oil in the gas turbine power plant. Herdin et al. [52] reported that the efficiency of gas turbine for electric generation using natural gas was 45%. In this paper, the efficiency of pyrolysis oil in gas turbines engine is assumed to be 42% which is the same as Jaramillo's dissertation.

3.6.3. Steam Turbine Generator. In this work, pyrolysis oil is being used as a replacement for coal and fuel oil in a steam turbine generator. Steam turbine generators use fuel combustion in a boiler to produce steam. Next, steam is injected into steam turbine to generate electricity. Normally, steam turbines have a lower efficiency compared to a reciprocating engine such as diesel engine or gas turbines but overall efficiency can be higher [53]. In order to operate the boiler with pyrolysis oil, some modification is needed to improve combustion stability. A support fuel is needed to start up the boiler. In case of low quality pyrolysis oil, support fuel is needed during operation. Pyrolysis oil has a longer flame than standard fuel oil. Schreiner et al. [54] investigated the use of biomass pyrolysis in the coal power plant. Their work showed promising result. The combustion of pyrolysis oil in the boiler is clean and efficient [55]. In this work, we assume that operating a coal power plant by using pyrolysis oil is going to give the same 33% efficiency as using coal in the operation [43]. Using pyrolysis oil as a substitution of fuel oil is assumed to have an efficiency of 34% [44].

Annual capital, operation and maintenance cost per kilowatt year for different power plants are shown in Table 13.

Table 13: Power generation capital, operation and maintenance cost per kWyr for different power plants [46].

System	Annual fixed capital cost, $/kWyr	Annual fixed operation and maintenance cost, $/kWyr
Diesel engine	75.00	3.00
Natural-gas-fired combustion turbine	32.00	3.25
Coal-fired steam cycle	120.00	6.25
Oil-fired steam cycle	96.00	5.50

4. Result and Discussion

This work views the switchgrass as a source of energy for different power plants. The LCA and LCC are used for understanding total emission and economics over the pyrolysis of switchgrass from cradle to grave. We started by calculating all impacts from growing switchgrass in an empty field to a final user, which is a power plant. The mass and energy balance is applied in this work to calculate the life cycle assessment.

4.1. Pyrolysis Plant Capacity Effect. In this study, the different capacities of pyrolysis plant from 100 ton per day to 5000 ton per day of switchgrass are assumed to be used to produce pyrolysis oil. The effect of the pyrolysis plant capacity will be shown in both the LCA and LCC. The total GHG emission, area used to grow switchgrass, switchgrass price, pyrolysis oil price, and electric price are affected by the capacity of pyrolysis plants. We assume that the distance from the pyrolysis plant to the power plant was 60 km.

4.2. Switchgrass Production. The switchgrass price per ton is considered by two life cycle stages: (1) switchgrass cultivation and harvesting and (2) transportation. In this analysis, the switchgrass is grown in a circular field, which has a land fraction of 0.441 of a field. This land faction is the same as the average agriculture land fraction for the USA [56].

Figure 4 shows that the price of switchgrass is increased by increasing the capacity of the pyrolysis plant. For example, if the pyrolysis plant capacity increases from 100 tons per day to 5000 tons per day, the switchgrass price increases more than one dollar per ton from $120.53 to $121.72 per ton. The price increase is due to the longer delivery distance for the switchgrass and the bigger area needed for switchgrass harvesting.

4.3. Area of Switchgrass Field. Normally, the area to grow switchgrass gets larger as the capacity of the pyrolysis plant increases. In this study, the loss of the switchgrass in transportation and processing is approximately 4% weight [57]. We chose a pole frame structure-enclosed on crushed rock as a storage system because it loses only 2% [35] weight of the switchgrass in storage. Even if the price of building storage in the pole frame is high, we lose less switchgrass from this storage. As a result, we need less area to grow it. The land

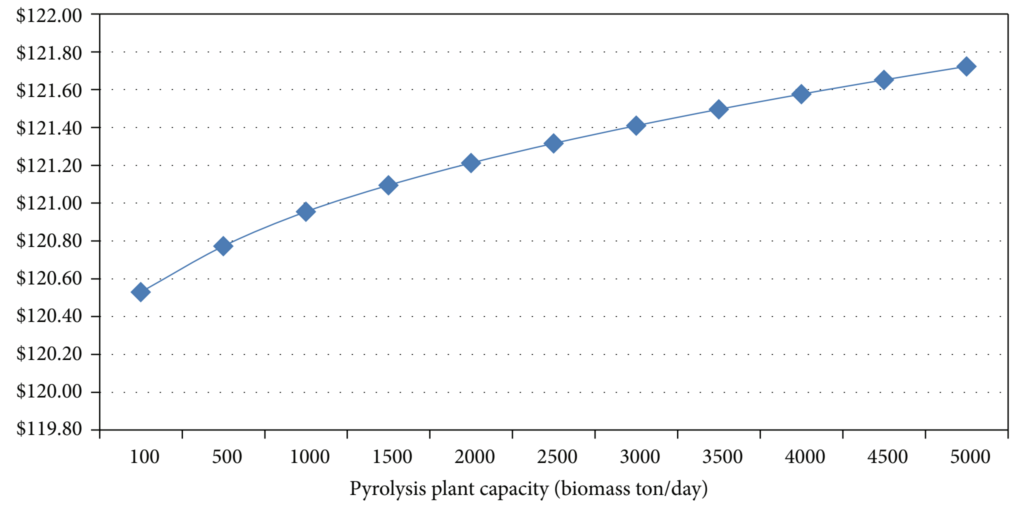

Figure 4: Switchgrass price versus pyrolysis plant capacity.

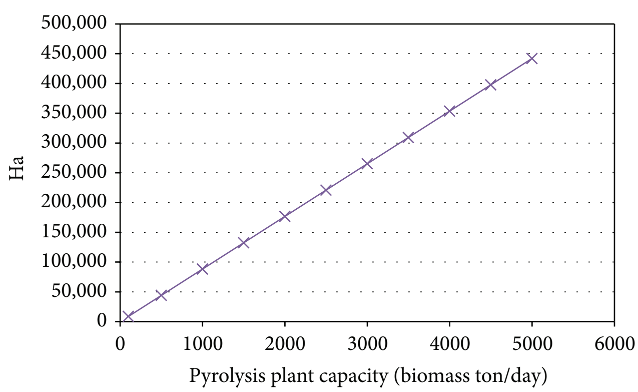

Figure 5: Area of switchgrass field varies by pyrolysis plant capacity.

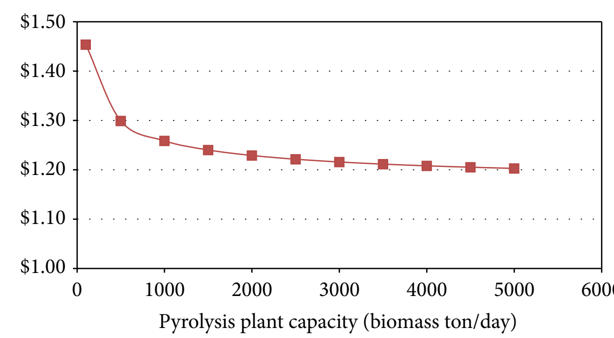

Figure 6: Pyrolysis oil price versus pyrolysis plant capacity.

fraction used for switchgrass was 0.441 in a circular shape field.

From Figure 5, the area is a linear function of the capacity. The area of switchgrass field is 8837.6 Ha for fulfill pyrolysis plant at capacity of 100 tons per day and the area is 441880 Ha in capacity of 5000 tons per day of pyrolysis plant. The 441880 Ha is a huge area that is even bigger than the land area of Rhode Island. The Rhode Island land area is 1034 square miles or 267805 Ha.

4.4. Pyrolysis Oil Production. In this study, in order to produce pyrolysis oil from switchgrass, there are three life cycle stages: (1) switchgrass cultivation and harvesting; (2) transportation; (3) storage. Pyrolysis plant produced three products: NCG, pyrolysis oil, and biochar. The ratio of pyrolysis oil produced is 60.7% w/w. NCG is 12.9% w/w and biochar is 11.3% w/w. The NCG and biochar are used in the pyrolysis plant as an energy source to operate the pyrolysis plant. Therefore, the net product from this plant is only pyrolysis oil, which is assumed to be sold to different power plants as a substituted energy source.

From Figure 6, the pyrolysis oil price decreases, while the pyrolysis plant size increases. The price of pyrolysis oil is $1.45 per gal at a capacity of 100 tons per day, while pyrolysis oil price reduces to $1.20 per gal at a capacity of 5000 tons per day.

4.5. Electricity Produced by Pyrolysis Oil in Different Power Plants. In order to produce electricity from switchgrass, we considered four life cycle stages: (1) switchgrass cultivation and harvesting; (2) transportation and storage; (3) pyrolysis production and transportation; (4) electric generator. There are four kinds of power plants: (a) diesel engine power plant; (b) natural-gas-fired combustion turbine power plant; (c) coal-fired steam-cycle power plant; and (d) oil-fired steam-cycle power plant. The Natural-gas-fired combustion turbine power plant is the most efficient plant having an efficiency of 42%, while the diesel engine power plant is the lowest efficiency at 32.4%. The coal-fired steam-cycle power plant and oil-fired steam cycle power plant have an efficiency of 33% and 34%, respectively.

From Figure 7, it can be concluded that the natural-gas-fired combustion turbine will produce a higher amount of electricity (11.44 Mw) than the diesel engine (8.83 Mw), when

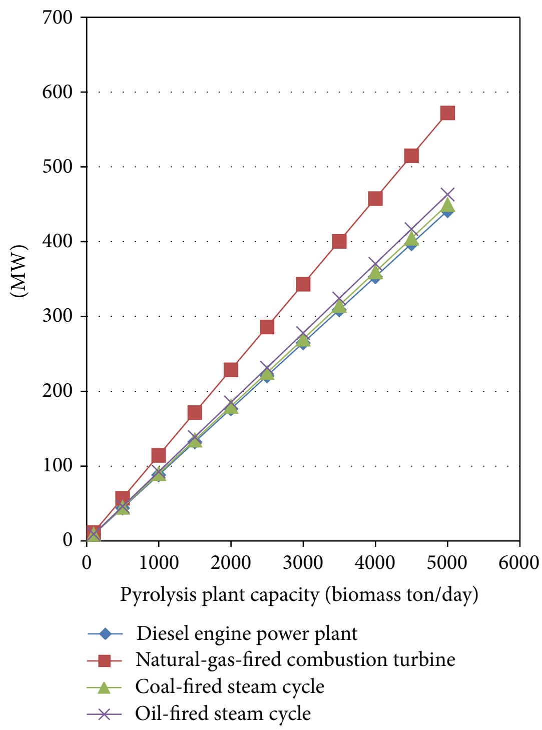

Figure 7: Electricity produced by different power plants varies with pyrolysis plant capacity.

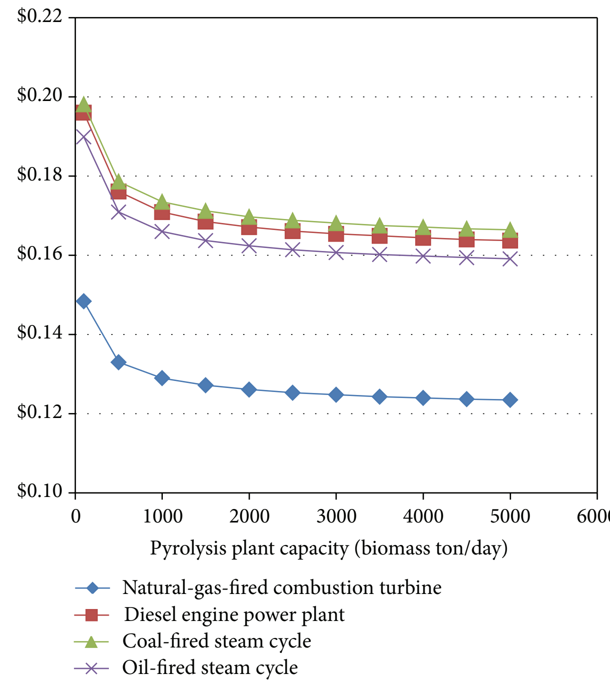

Figure 8: Price of electricity in different power plants versus pyrolysis plant capacity.

both are supplied with equal amounts of pyrolysis oil from a plant of capacity 100 tons per day. At a plant capacity of 5000 tons per day, the natural-gas-fired combustion turbine produces 572.13 Mw, while the diesel engine could produce 441.36 Mw. With 572.13 Mw of electricity or 5011.86 million kilowatt-hours, it can provide enough electricity for all the state of Hawaii requirement. From the report of the U.S. Energy Information Administration in 2012 [58], Hawaii consumed 4723 million kilowatt-hours.

From Figure 8, it can be concluded that because the natural-gas-fired combustion turbine is the most efficient power plant compared with others, it produces the cheapest electricity. The pyrolysis plant capacity of 100 tons of switchgrass can supply the natural-gas-fired combustion turbine to produce electricity at a price of $0.15 per kwh. The price could drop to $0.12 per kwh with the pyrolysis plant at a capacity of 5000 tons per day. The highest electric price was produced by the coal-fired steam cycle since the capital cost and maintenance cost are the highest. The electric cost was $0.20 per kwh for the pyrolysis plant at capacity of 100 tons per day. The price could drop to $0.17 per kwh for the pyrolysis plant at capacity of 5000 tons per day. From the U.S. Energy Information Administration [59], the average electricity cost in the United States in 2011 was $0.10 per kwh. From the analysis, the cost of electricity from combustion of biooil is higher than the normal average electricity cost in the United States.

4.6. GHG Emission per kwh. The GHG emission per kwh is shown in Figure 9. Because the average agricultural land in the US is about 44.1% [56] of the entire US land, we assume that the average percentage of land use to grow switchgrass is 44.1% (land fraction). The land shape was assumed to be circular. The total GHG emission per kwh of using pyrolysis oil from switchgrass is negative because carbon dioxide is sequestrated into the soil while growing switchgrass. The value of soil organic compound increasing at the rate of 0.49 ton/acre/year is used for the first two years of establishment and reseeding case [42] and 1.5 ton/acre/year is used for mature crop case. The natural-gas-fired combustion turbine seems to have higher GHG emission per kwh because this power plant was assumed to have the highest efficiency at 42% while others have efficiency around 32–34%. In order to calculate GHG emission per kwh, firstly we calculate an accumulation of GHG emission from starting of seeding year through the end of switchgrass live cycle at the eleventh year. Secondly, we average the total GHG emission per kwh, which is produced during nine years of operation of the power plant.

As demonstrated in Figure 9, because the natural-gas-fired combustion turbine is the most efficient power plant, which generated most electricity, its GHG emission per kwh is the highest. However, all the GHG results are negative which mean the GHG is adsorbed to the system. Results from Figure 9 show that the pyrolysis plant capacity almost has no effect, or only a small increasing effect, on GHG emission while the capacity gets higher. From the results of LCA, pyrolysis of switchgrass was totally clean energy which can reduce the GHG emission.

4.7. Distance from Pyrolysis Plant to Power Plant Effect. From Figure 10, the price of pyrolysis oil is higher if the

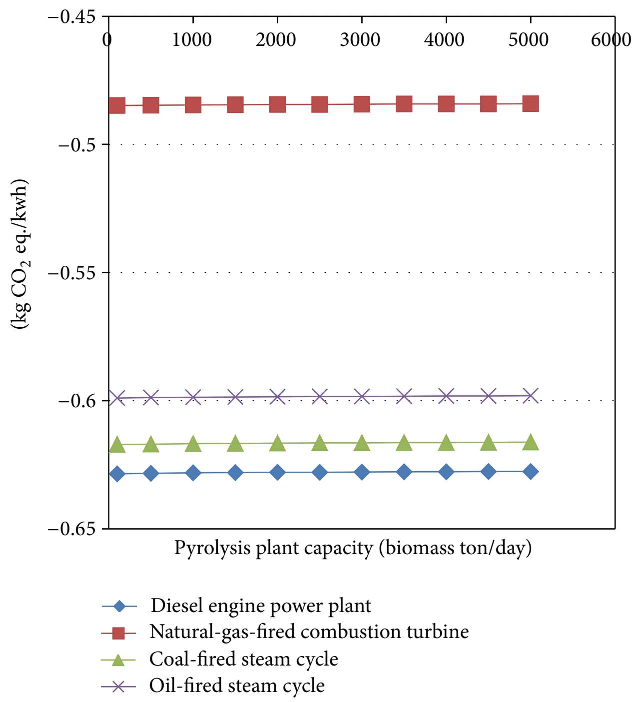

Figure 9: Variation of total emission (of different power plants) with pyrolysis plant capacity.

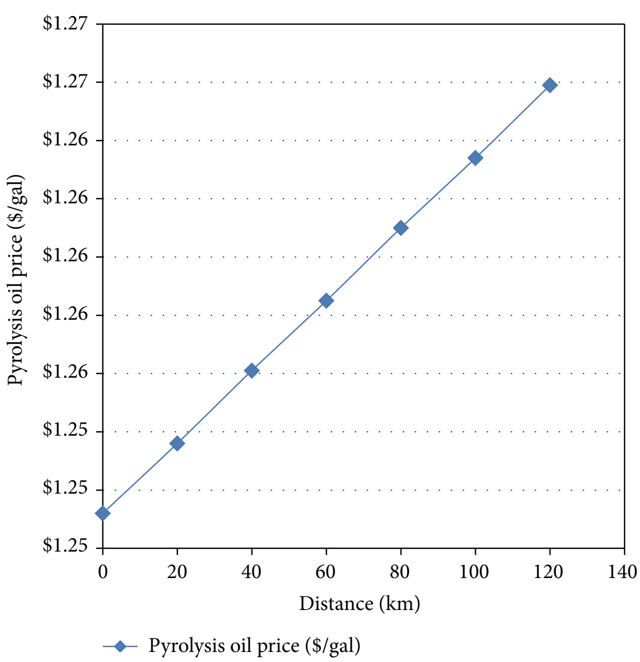

Figure 10: Dependence of price of pyrolysis oil on distance from pyrolysis plant to power plant ($/gal).

distance between the pyrolysis plant and the power plant is larger. However, the pyrolysis oil price varies slightly with the distance. At zero distance, which meant the pyrolysis plant and the power plant are at the same location, pyrolysis oil price is $1.251 per gal. When the distance between the

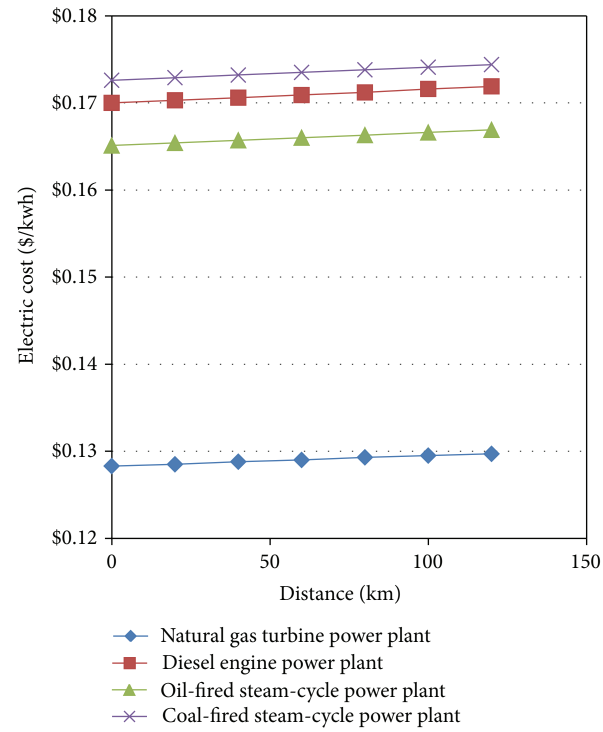

Figure 11: Dependence of electric cost on distance between pyrolysis plant and power plant ($/kwh).

pyrolysis plant and the power plant is 120 km, the pyrolysis oil price is $1.266 per gal.

In Figure 11, the distance from the pyrolysis plant and the power plant had a minor effect on the electricity cost. The type of power plant is the determining factor for decreasing electricity cost. The natural gas turbine power plant produces the cheapest electricity. At zero distance, the electricity cost was 12.83 cent per kwh. At 120 km, the electricity cost is 12.97 cent per kwh. The most expensive electricity cost comes from substituting pyrolysis oil into the coal-fired steam-cycle power plant. At zero distance, the electricity cost is 17.26 cent per kwh. At 120 km, the electricity cost increases to 17.44 cent per kwh. At these electricity costs, substituting pyrolysis oil in the power plant is not competitively priced compared to fossil fuel.

From Figure 12, the distance between the pyrolysis plant and the power plant has a minor effect on GHG emission per kwh. The type of power plant has affected GHG emission per kwh more so than the distance. All of the power plants, which used pyrolysis oil substituted for fossil fuel, had negative GHG emission. The most negative GHG emission per kwh comes from the diesel engine power plant. At zero distance, the GHG emission per kwh of the diesel engine power plant is −0.6251 kg CO_2 eq./kwh. At 120 km, the GHG emission per kwh is −0.6312. The natural gas turbine power plant has less negative GHG emission compared to other power plants. At zero distance, the GHG emission per kwh is −0.4869 kg CO_2 eq. per kwh. At 120 km, the GHG emission per kwh is −0.4822 kg CO_2 eq. per kwh.

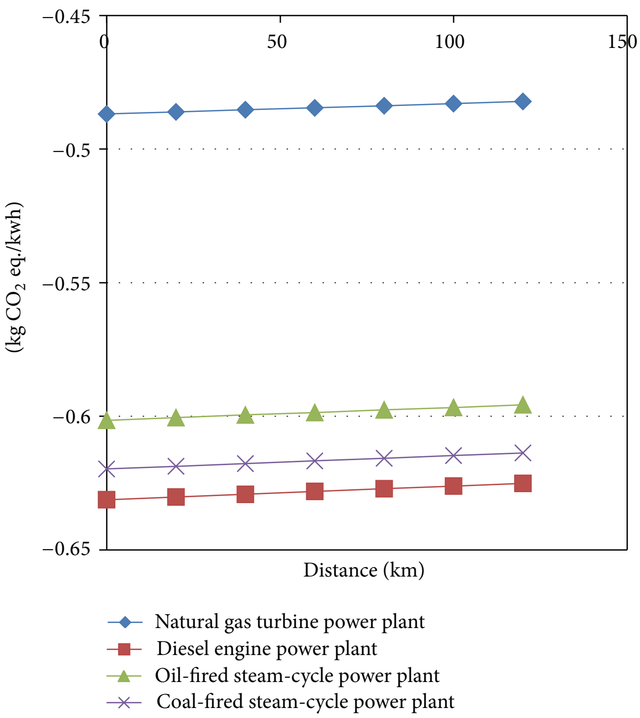

FIGURE 12: Dependence of total GHG emission on distance between pyrolysis plant and power plant (kg CO_2 eq./kwh).

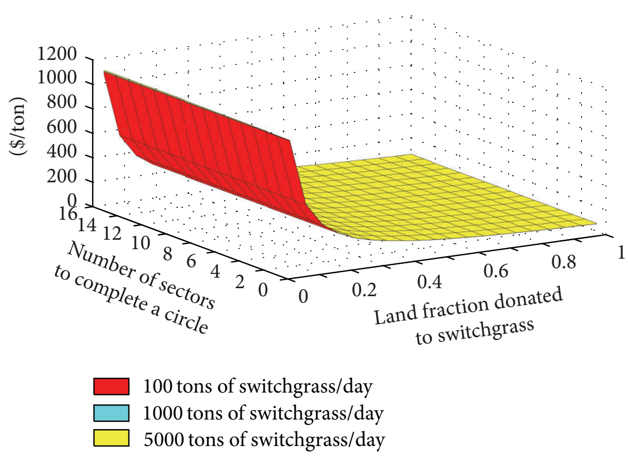

FIGURE 13: Dependency of switchgrass price on land fraction and field shape.

4.8. Land Fraction and Field Shape Effect. In this study, the land fraction and field shape effect has been analyzed. The land fraction and field shape have an effect on switchgrass price, pyrolysis oil price, electricity cost, and GHG emission per kwh. The field was divided into numbered sectors to complete a circle (n). The $n = 1$ represented a complete circles-like shape. The $n = 10$ to 16 represented the long, narrow shapes of the divided sectors.

4.8.1. Land Fraction and Field Shape Effect on Switchgrass Price. From Figure 13, the land fraction used for switchgrass

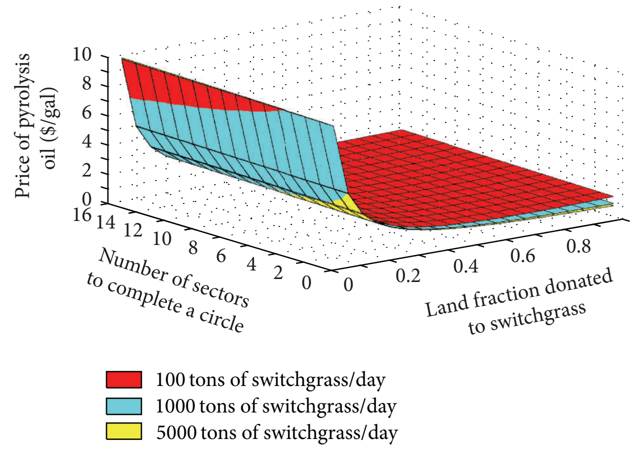

FIGURE 14: Dependency of pyrolysis oil price on land fraction and field shape.

and the number of sectors to complete a circle affect switchgrass price. The capacity of the pyrolysis plant has a small effect compared to the land fraction used for switchgrass. The capacity of the pyrolysis plant at 1000 tons per day is chosen as a representative of this calculation. If all the land is used for switchgrass (100%) and the field shape is circular, the switchgrass price can reduce to $53.48 per ton. From this information, the most important parameter is land fraction used for switchgrass. The switchgrass should be grown in an isolated empty field, separated from other plant species. This can lower the price of switchgrass.

4.8.2. Land Fraction and Field Shape Effect to Pyrolysis Price. From Figure 14, the land fraction used for switchgrass and number of sectors to complete a circle affect pyrolysis price. The capacity of the pyrolysis plant has some effects on the pyrolysis oil price. If pyrolysis plant capacity is 5,000 tons per day, pyrolysis oil price can be as low as $0.734 per gallon if the land fraction used for switchgrass is 1 and the number of sectors to complete a circle which is 1.

4.8.3. Land Fraction and Field Shape Effect Electricity Cost. In Figures 15, 16, 17, and 18, the land fraction utilized to grow switchgrass and the number of sectors to complete a circle affect pyrolysis price. The capacity of pyrolysis plant also has an effect on the pyrolysis price.

The coal-fired steam-cycle power plant produces the most expensive electricity cost per kwh. If pyrolysis plant capacity is 5000 tons per day, the electricity cost will be dropped to $0.102 per kwh, when the entire land area is utilized to grow switchgrass (land fraction = 1) and the field shape is circular ($n = 1$).

The natural gas turbine power plant produces the cheapest electricity cost per kwh. If pyrolysis plant capacity is 5000 tons per day, the electricity cost will be dropped to $0.077 per kwh, when the entire land area is utilized to grow switchgrass (land fraction = 1) and the field is circular ($n = 1$).

The oil-fired steam-cycle power plant produces a cheaper electricity cost than the diesel engine power plant. Based on

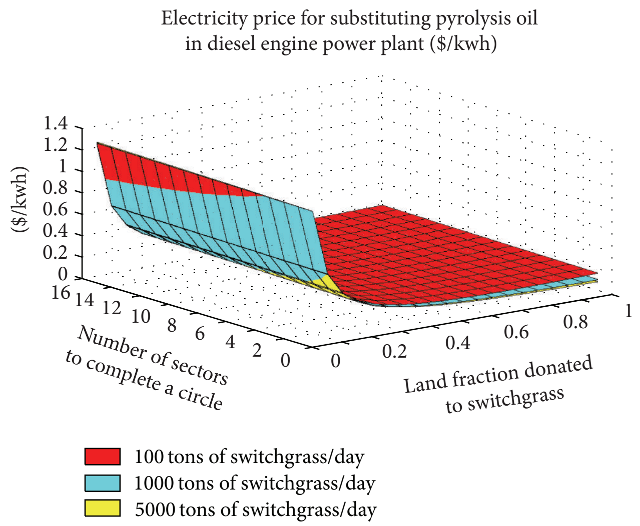

Figure 15: Electricity price for substituting pyrolysis oil in diesel engine power plant varies with land fraction and land shape.

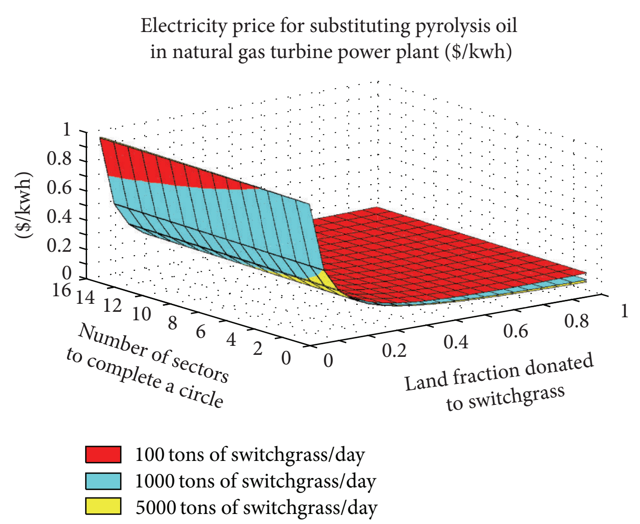

Figure 16: Electricity price for substituting pyrolysis oil in natural gas turbine power plant varies with land fraction and land shape.

this analysis, the natural gas turbine power plant is the most promising plant to utilize pyrolysis oil since it produces the cheapest electricity cost. The electricity cost at 7.70 cent per kwh is preferable since it is a competitive cost to conventional energy resources. According to the U.S. Energy Information Administration [59], the average electricity cost in the United States in 2011 was $0.10 per kwh. The electricity cost at 7.70 cent per kwh can be obtained only if the entire field is utilized to grow switchgrass. However, it is impossible to fill such a huge area (441880 Ha) with a sea of switchgrass. The efficient management of growing, transportation, storage and pyrolysis, and choosing a suitable power plant are all required in order to make switchgrass energy sustainable and competitive with conventional energy sources.

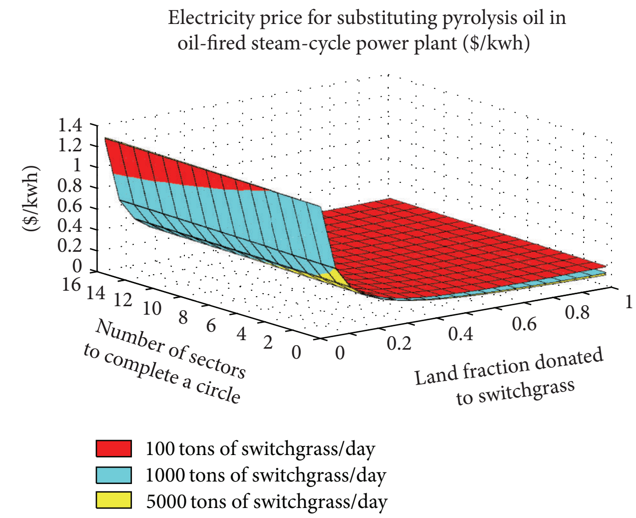

Figure 17: Electricity price for substituting pyrolysis oil in oil-fired steam-cycle power plant varies with land fraction and land shape.

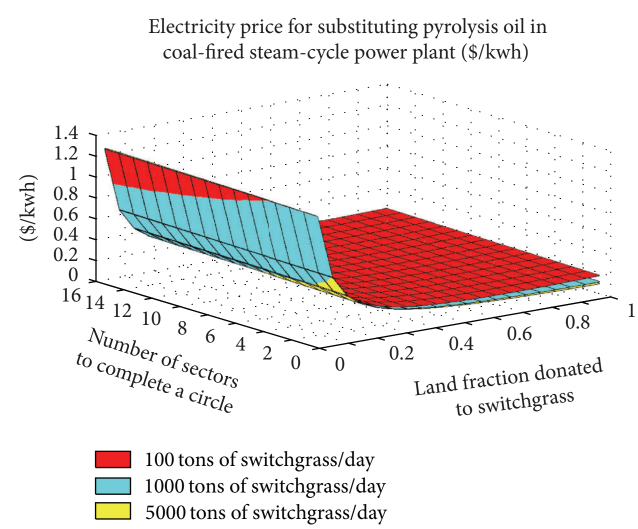

Figure 18: Electricity price for substituting pyrolysis oil in coal-fired steam-cycle power plant varies with land fraction and land shape.

4.8.4. Land Fraction and Field Shape Effect on the Total GHG Emission. Figures 19, 20, 21, and 22 show the GHG emission per kwh. The land fraction used for switchgrass, number of sectors to complete a circle, and type of power plant have effects on the GHG emission. The pyrolysis plant capacity has a small effect on the GHG emission. In Figures 19 to 22, four power plants are shown. Operating all of the power plants with pyrolysis oil from switchgrass has negative GHG emissions. The most negative GHG emission per kwh comes from the diesel engine power plant. The least negative GHG emission per kwh comes from the natural gas turbine power plant.

For the diesel engine power plant, if all the land is used to grow switchgrass (land fraction = 1) and the field is circular

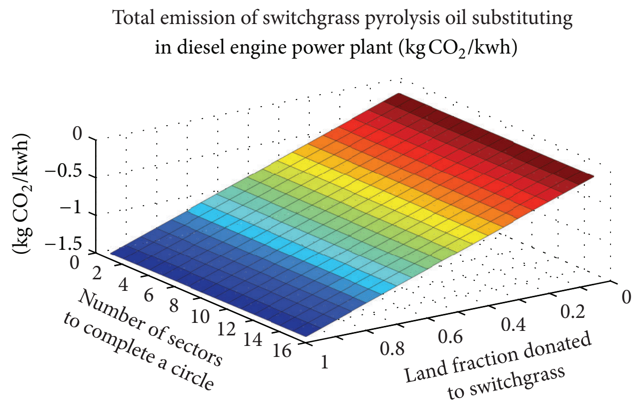

FIGURE 19: Total emission of switchgrass pyrolysis oil substituting in diesel engine power plant varies with land fraction and field shape.

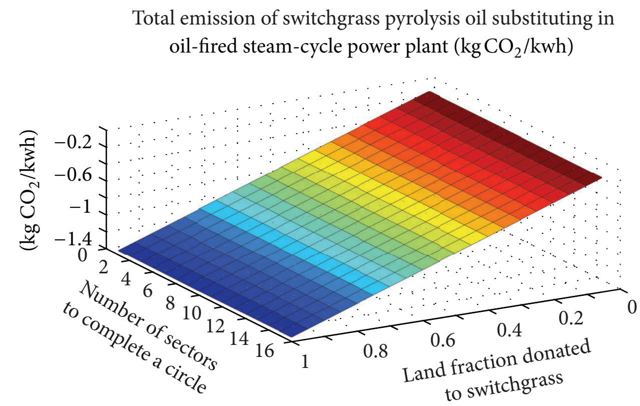

FIGURE 21: Total emission of switchgrass pyrolysis oil substituting in oil-fired steam-cycle power plant varies with land fraction and field shape.

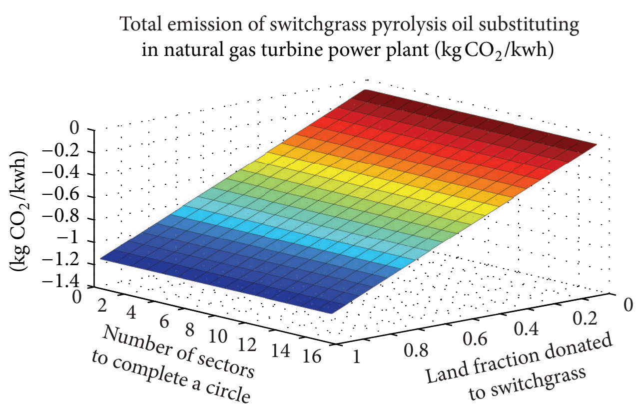

FIGURE 20: Total emission of switchgrass pyrolysis oil substituting in natural gas turbine power plant varies with land fraction and field shape.

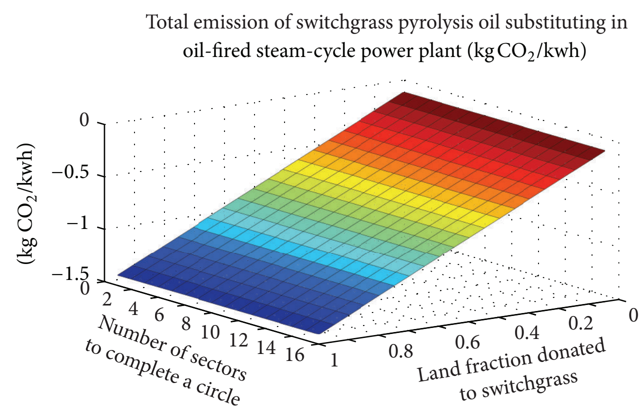

FIGURE 22: Total emission of switchgrass pyrolysis oil substituting in coal-fired steam-cycle power plant varies with land fraction and field shape.

($n = 1$), the GHG emission is −1.4321 kg CO_2 eq. per kwh—the lowest GHG emission.

For the natural gas turbine power plant, if all the land is used to grow switchgrass (land fraction = 1) and the field is circular ($n = 1$), the GHG emission is −1.1037 kg CO_2 eq. per kwh.

In this study, the land fraction used for switchgrass was the most important parameter for reducing GHG emissions. Comparing the GHG emission of pyrolysis oil from switchgrass to that of conventional fossil fuels (reported in Table 14), the GHG emission from pyrolysis oil was desired. All of the power plants that used pyrolysis oil from switchgrass were environmentally friendly since total GHG emission from the process was negative. Based on this analysis, the switchgrass field adsorbed more GHG than was emitted from other processes.

TABLE 14: Life cycle assessment of greenhouse gas emissions (kt eq. CO_2 per Twh) [47].

	Low emission rate kt CO_2 eq. per TWh
Diesel engine power plant	649
Natural gas turbine power plant	422
Oil-fired steam-cycle power plant	841
Coal-fired steam-cycle power plant	941

5. Conclusion

This study is based on biooil produced through fast pyrolysis. The switchgrass was grown in fields of different shapes and land fractions. life cycle assessment analysis and Life cycle cost analysis were performed on a system which consisted of cultivating and harvesting, transportation and storage, pyrolysis, transportation, and power generation. The GHG emission from the system was negative. Based on life cycle assessment, the power generation using pyrolysis oil is environmentally friendly since it reduces GHG emissions. On the other hand, life cycle cost analysis reveals that the electricity cost per kwh is higher than the conventional technology which uses fossil fuels. However, based on the analysis, the electricity cost from pyrolysis oil could be competitive if we can utilize the system with the cheapest scenarios. A circular field entirely filled with switchgrass is optimal for reducing electricity cost because of lower cost of cultivation, harvesting, and transport. A circular field with a pyrolysis plant capacity of 5000 tons per day using the natural gas turbine power plant could have an electricity cost as low as 7.70 cent/kwh. However, power generation from switchgrass requires a huge amount of land. We assumed that the land fraction utilized to grow switchgrass is the same as the average agriculture land fraction in the USA, which is 44.1%. In order to provide enough switchgrass for a pyrolysis plant capacity of 5000 tons per day, a large land area size of 1706.11 square miles, which is even bigger than Rhode Island, is required. In the future, when carbon credit is fully utilized, pyrolysis oil could be more competitive for the benefit of carbon credit.

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