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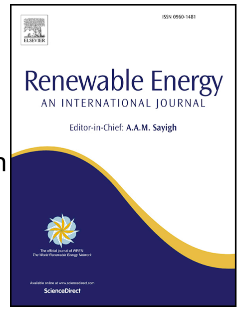

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Stochastic techno-economic analysis of electricity produced from poplar plantations in Indiana

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Abstract

This study evaluates the economic and global-warming potential for a 100% biomass direct-fire biopower plant in Indiana using short-rotation coppice poplar (*Populus* spp.) as a feedstock. The poplar yield and moisture content data were collected from an actual field trial conducted in southern Indiana beginning in 2013. Monte-Carlo simulation was applied to account for uncertainty in three parameters (poplar yield, moisture content, and planting costs).

We found that the biopower plant is economically infeasible in Indiana, as the estimated system break-even price (21.5 cents/kWh) is six times higher than the current wholesale electricity price in Indiana. Based on the LCA analysis, we found that this pathway has negative net emissions (-1.14 kg CO_2 eq/kWh), due to carbon sequestration. As a coal-intensive power-generating state, Indiana would require a carbon tax above $93.5/ton CO_2-equivalent to make the biopower plant competitive with other types of power plants (coal and natural gas).

This analysis was based on average-quality land. We then conducted a sensitivity analysis using poor- and high-quality land. There are small, statistically significant differences between land types, but likely they are not economically significant because the data we have for the three land rents are subject to high uncertainty, which could not be quantified.

Keywords: stochastic techno-economic analysis; life-cycle assessment (LCA); short-rotation coppice (SRC) poplar; biopower; renewable electricity

Nomenclature

BBFB	Biomass Bubbling Fluidized Bed
DOE	Department of Energy
EGU	Energy Generating Unit
GHG	Greenhouse Gas
GREET	Greenhouse Gases, Regulated Emission, and Energy Use in Transportation model
GWP	Global Warming Potential
IRR	Internal Rate of Return
LCA	Life Cycle Assessment
NPV	Net Present Value
SRC	Short Rotation Coppice
SWPAC	Southwest Purdue Agricultural Center

1. Introduction

Electricity produced from biomass is renewable and has the potential to mitigate greenhouse gases (GHG) compared to coal-fired power plants. Carbon emission reductions are one of the driving forces behind biopower electricity capacity investments [1–3]. The biggest issue has been to overcome its economic infeasibility, relative to fossil electricity pathways through government policy, with the goal of renewable energy expansion.

Poplar (*Populus* spp.) shows promise as a dedicated bioenergy crop. Short-rotation coppice (SRC) is a special production method that exploits rapid shoot re-growth from the stumps of trees that have been cut near ground level. The main advantage of SRC poplar is that this fast-growing tree can be coppiced every three years for up to eight harvesting cycles, without the need to replant [4]. However, there is large variability in poplar yield, depending on the planting site and genotype [5–10]. Therefore, knowing yield in the area where the biomass production is expected to occur is the most important factor for project evaluation.

The Indiana power-generation system is heavily coal-dependent; coal-fired power plants generate more than 70% of total utility-scale electricity. The resulting low electricity price has hindered large renewable penetration in Indiana, with only five percent of the power being generated from renewable resources.

The objective of this study is to examine the economic feasibility, global-warming potential (GWP) of a SRC poplar-fed biopower plant in Indiana. Utilizing biomass yields obtained from a field trial conducted in southern Indiana, this study models a 50-MW direct-firing combustion biopower plant in that locale using regionally tailored data from the U.S. Department of Energy (DOE) [11]. For the economic analysis, all costs needed to operate the system are accounted for, including: poplar production fieldwork costs, biomass transportation, and power-plant operating costs. To estimate the net carbon emission of this system, compared to the conventional coal-power plant, life-cycle assessment (LCA), including poplar cultivation-related emissions, poplar biogenic emissions (e.g. carbon sequestration), and power-plant emission were evaluated.

2. Methodology

2.1 Techno-economic analysis

The first section covers all the components of the economic analysis for the complete poplar-to-power pathway, including the experimental poplar data on which the poplar yields and moisture are based, optimization of poplar plantation size, and the timeline. Subsequent sections cover the poplar biomass production costs, power plant costs, and an economic analysis of the entire system.

2.1.1 System design

2.1.1.1 Biomass yield and moisture content data

In 2013, the SRC poplar (60 genotypes, 6-10 ramets per genotype in each of four replicate blocks) were planted at the Southwest Purdue Agricultural Center (SWPAC) located in southern Indiana, approximately five miles north of Vincennes. Trees were harvested after three years, and yield from the highest-performing third of the genotypes was utilized this study. The mean yield and moisture content were 25.15 dry tons/ha and 54.6%, respectively. In parametrization yield, the following two adjustments were applied: a yield gap and second-harvest yield changes. The yield gap is to reflect the diminished yield in commercial plantings relative to research trials, due to the lack of timely field operations and resource limitations [12,13]. We reduced the SWPAC yield by 15% to account for the research plot-farmer yield gap. In addition, 30% higher yield was assumed in the second and subsequent harvests. The lower yield expectation in the first harvest is because a significant amount of the plant's resources are used for the development of a root system during early establishment, rather than volumetric stem growth [14]. Based on the adjustments, the final mean yield used for this study was 21.37 dry ton/ha in the first harvest and 27.79 dry ton/ha from the second harvest.

2.1.1.2 Power plant biomass demand and poplar land area needed

Our calculations assume a 50-MW biopower plant with a biomass bubbling fluidized bed (BBFB) boiler and a steam turbine engine [11]. Based on the required heat rate (14.2 MJ/kWh) at 60% of full capacity for a biopower plant and poplar energy content (high heating value 19.3 MJ/dry kg), the annual average biomass need was estimated to be 193,842 dry tons.

Given this estimate of biomass quantity, it is possible to estimate the size of the poplar plantation required to meet this need. Due to the unavoidable uncertainty in yield, the harvested biomass may be insufficient in some years, if the calculated land area was the minimum needed to meet the annual biomass demand of the power plant. Insufficient biomass production could result in a significant loss because an idle power plant will not be recovering its high capital investment. To minimize the risk of biomass shortage, we could apply a conservative production design by purposely allocating a larger land area to produce more biomass than is needed by the power plant. However, excessive production can also harm the system economics if the surplus of poplar chips are not sold. Given these economic tradeoffs, we used @Risk Optimizer [15] to find the optimal biomass production that would lead to the lowest system break-even price. With @Risk Optimizer software, the selected variables are optimized to satisfy the optimization goal (e.g., minimum, maximum or target value) while accounting for uncertainty parameters based on a Monte Carlo simulation. During this numerical optimization, each trial improves the model solution by changing the combination of optimization variables to achieve the target goal. The obtained optimization production level was 0.83% higher than the biomass demand of the power plant. Therefore, the poplar plantation must be large enough to produce 195,447 dry tons on average. Occasional shortfalls in wood chips would be made up through market purchases.

To provide this quantity annually, 7,815 ha are needed. Because of the length of the harvesting cycle, this land area can only produce sufficient biomass every three years. In other words, to produce sufficient biomass annually, three fields need to be operated simultaneously, with one-third of the trees being harvested at one-year intervals. Therefore, the total land area needed is 23,446 ha.

2.1.1.3 System operation timeframe

Another key issue for seamless system operation is to produce biomass annually for the 48-year life expectancy of the biopower plant. Because we only expect eight three-year harvesting cycles from the first poplar planting (to year 24), a second planting will be needed. To have uninterrupted biomass production, there needs to be an overlap between the establishment of the second planting site and the final harvest on the first planting site (see SOM 1).

2.1.2 Biomass production costs

Given the large scale of the poplar plantations, it is imperative to have efficient field design to minimize biomass production costs. It is also important to account for all machinery, labor, and material costs associated with plantation establishment and harvesting. The needed machinery includes: a tractor attached to a planter and a refrigerated truck for the planting activity; a harvester and collection vehicle (tractor and wagon set) for harvesting; and a truck for transporting the biomass [16]. The amount of equipment needed to complete the field work in a timely manner is based on machine operation capacities, which are shown in Table 1.

Table 1 Poplar field operation configuration.

Activity	Value	Unit	Reference
Planting time	3	months/year	Assumption
Planter speed	0.8	hour/ha	[17]
Planting equipment	10	planters/year	Poplar model calculation
Harvesting time	10	months/year	Assumption
Harvester operation rate	0.6	hour/ha	[18]
Harvester equipment	3	harvester/year	Poplar model calculation
Collector equipment	9	collector/year	Poplar model calculation
Transport distance	21.2	km	Author calculated

Certain assumptions regarding plantation-maintenance practices were made to provide sufficient nutrients for the poplar trees (Table 2). In the SWPAC field study, the effects of fertilization and irrigation were not quantified [19]. However, fertilizer applications were planned for the current study because nutrients will likely become limiting, considering the high planting density and harvesting frequency.

Table 2 Plantation maintenance assumptions.

Activity	Value used	Unit	Reference
Planting density	18,000	stems/ha	[20,21]
Vegetative propagule	Yes		[21]
Fertilization application[1]	Yes		[22]
▪ Nitrogen	20	kg/ha	[22]
▪ Phosphoric acid	6	kg/ha	[22]
▪ Potassium oxide	5.3	kg/ha	[22]
Herbicide	Yes		
▪ Pre-plant herbicide[2]: glyphosate	4.7	liter/ha	Calculated
▪ Post-plant[3]/post-harvesting[4] herbicide: glyphosate	2.3	liter/ha	Calculated
▪ Post-plant[3]/post-harvesting[4] herbicide: Goal® 2XL	5.9	liter/ha	Calculated

Insecticide[5]	Yes		
▪ Sevin® XLR plus	3.5	liter/ha	Calculated
Irrigation	No		

[1]Fertilization is applied in the year after planting and every harvest year.
[2]Pre-planting herbicide is applied one year earlier than planting.
[3]Post-planting herbicide is applied for two consecutive years after planting
[4]Post-harvesting herbicide is applied in the year following each harvest.
[5]Insecticide is applied in the year after planting and one year before each harvest.

Average cost parameters for poplar cultivations are shown in Table 3. Additional details for each category are documented in SOM 2. All costs needed for field operations were obtained from the relevant literature and converted to 2016 dollars. The plantation maintenance parameters (e.g. fertilizer, herbicide, etc.) were calculated using the retail price of the products specified. These parameters were inserted into an Excel spreadsheet that is part of our poplar economic model.

Table 3 Input cost parameters for poplar biomass production.

Type	Parameters	Value	Unit
Planting	Land/Administration	342	$/ha
	Site management	366	$/ha
	Equipment per hectare costs	116	$/ha
	Labor per hectare costs	67	$/ha
Harvesting	Equipment per hectare costs	464	$/ha
	Labor per hectare costs	108	$/ha
Transportation	Equipment per hectare costs	66	$/ha
	Labor per hectare costs	95	$/ha

2.1.3 Power plant operation

The assumed 50-MW biopower plant uses BBFB direct (100% biomass) combustion technology. This is a mature technology which has been used successfully in numerous commercial-scale operations [23]. Table 4 illustrates a summary of technical properties and assumptions.

Table 4 Biopower plant technical assumptions.

Cost types	Value	Unit	Reference
Feedstock throughput	193,842	dry ton/year	Calculated
Electricity generation	262,800	MWh/year	Calculated
Heat rate	14.2	MJ/kWh	[11]
Capacity	50	MW	[11]
Capacity factor[1]	60	%	Author determined
Full capacity operation	8,760	hours/year	Author determined
Construction time	3	years	Author determined
Plant lifetime	48	years	Author determined
Startup period	0.5	years	[24]
Startup production rate	50	%	[24]
Startup variable expense	75	%	[24]
Startup fixed expense	100	%	[24]

[1]Capacity factor means that we assume the plant would operate at 60% of its rated capacity on average. This value is typical for plants of this type.

Indiana-adjusted capital and operating costs (non-fuel) for this type of facility were obtained from the DOE [11]. The biomass purchase costs were obtained from the poplar model's estimate of the poplar growers' break-even price, which includes a 10% markup on total costs, to provide a profit for the grower. Table 5 presents a breakdown of the power-plant costs. The capital costs were spread over the three years of construction (8%, 60%, and 32%, respectively). As the only product, electricity was assumed to be sold to Indiana power grid at the wholesale electricity market price.

Table 5 Biopower plant economic parameters.

Cost types	$ in 2016	Unit	Reference
Total project capital investment	242.3	$M	[11]
Fixed operating costs	110	$/kw/year	[11]
Variable operating costs (non-fuel)	4.2	$/MWh	[11]
Biomass purchase price (poplar)	138	$/dry ton	Poplar model calculated
Electricity price	3.674	Cents/kWh	[25]

2.1.4 Stochastic parameters

Due to the uncertainties inherent in biomass production and energy markets, we chose to do the analysis stochastically to incorporate this uncertainty in the key input parameters [24]. Among various metrics commonly used for the project evaluation, such as net present value (NPV) and internal rate of return (IRR), we focused on break-even price because new renewable projects (e.g. a biopower plant) tend to have negative profitability, due to the low cost of fossil fuels. In addition, break-even price delivers useful information to investors by showing the product price needed to recover production costs. Also known as the minimum selling price, the break-even price is the output price at which total revenues are equal to total expenses; it is calculated as the output price at which NPV for net benefits of the entire system is zero [24]. Eq. 1 represents the NPV formula used to calculate total net benefits.

$$NPV = \sum_{t=0}^{n} \frac{Q_t * P_t}{(1+r)^t} - \sum_{t=0}^{n} \frac{C_t}{(1+r)^t} \qquad \text{Eq. 1}$$

where Q_t is the output quantity at time t, P_t is the output price at time t, C_t is the cost at time t, and r is the discount rate [24]. The first term refers to NPV of total benefits and the second term refers to NPV of total costs. By setting this to zero, we can derive an expression for the break-even price (Eq. 2) [24].

$$Breakeven\ price(P_t) = \frac{\sum_{t=0}^{n} \frac{C_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{Q_t}{(1+r)^t}} \qquad \text{Eq. 2}$$

We calculated the break-even price using an add-in from the software @Risk add-in [15].

Moreover, the main output of this study, is the development of a break-even price distribution, instead of generating one break-even price for the system. This is because the break-even price distribution incorporates various uncertainties attached to the new system, thus increasing the usefulness of the project [24]. We applied Monte-Carlo stochastic analysis method with a large number of iterations (1,000 in our study) to generate this distribution by obtaining the break-even price with each iteration. For this simulation, we selected three stochastic parameters to impose variance on data. The parameters were chosen because they influence system economics, they are uncertain, and data were available. They included biomass yield, moisture content, and planting cost. The distribution of yield and moisture content was based on the SWPAC field data and commercial poplar production data [18]. To avoid extreme values in simulations, the yield distribution used a PERT distribution based on the truncated original distribution at a 5% significance level. We also incorporated increasing yield uncertainty for harvests after the second one. In the literature, no consensus exists for predicting yield, as harvests occur multiple times. Some studies found an increasing yield pattern after the second harvest [10,26,27], whereas others showed a decreasing yield [9,28]. To incorporate the unpredictability of SRC yield pattern in rotations, we used an increasing uncertainty by assuming a yield standard deviation increasing by 3% for each harvest after the first two harvests. Moisture content distribution was bounded at 5% and 95% of the normal distribution. Due to the unavailability of distribution of real markets, planting costs were assumed to vary following a PERT distribution (minimum of 70%, most likely 105%, maximum of 130%) [29]. Table 6 shows the final distribution sets for these three parameters.

Table 6 Distribution of the stochastic parameters.

Stochastic parameter		Lower bound	Mean	Upper bound	Distribution
Poplar yield (unit: dry ton/ha)	1st cut	16.01	21.37	26.73	PERT
	2nd cut	20.81	27.79	34.75	PERT
	3rd cut	20.59	27.79	34.96	PERT
	4th cut	20.38	27.79	35.18	PERT
	5th cut	20.17	27.79	35.39	PERT
	6th cut	19.92	27.79	35.62	PERT
	7th cut	19.69	27.79	35.85	PERT
	8th cut	19.46	27.79	36.09	PERT
Poplar moisture content (unit: %)		50.98	54.60	58.22	Normal
Planting costs (unit: %)		70	105	130	PERT

2.1.5 Economic and financing assumptions

Similar economic and financing assumptions were used for the poplar plantation and power generation, as shown in Table 7. Income from the power plant operation was taxed, but the firm could make use of tax credits when the taxable income is negative. Taxes were not applied for the poplar plantation because agricultural tax rates are quite low, and sensitivity analysis showed it would not affect our results.

Table 7 Economic model assumptions.

Parameters	Value	Unit
Real discount rate	10	%
Inflation rate	2	%
Equity	60	%
Loan	40	%
Loan term	10	years
Loan interest rate	8	%
Income tax[1]	19.6	%
Depreciation term[1]	7	years
Depreciation method	Doubling declining balance	

[1]Loan interest payment and depreciation are exempted from taxable income estimation.

2.2 GWP emission analysis

Life-cycle assessment is a quantification method for evaluating environmental emissions, which tracks emissions of the entire energy system. This method is frequently used to evaluate the environmental performance of renewable technologies compared to conventional fossil technologies. In this study, we conducted LCA analysis of poplar-fed direct biopower system by focusing on GWP emissions, which were calculated as carbon dioxide equivalent (CO_2 eq.) accounted for three types of GHGs: CO_2, methane (CH_4), and nitrous oxide (N_2O). We identified three main sources of emissions in this biopower-plant system: 1) poplar cultivation emissions, 2) biogenic emissions sequestration, and 3) power plant operating emissions. The first and third emissions are always positive amounts, whereas the second emission captures emission-reduction effects, due to carbon-sequestration. The following three sections describe each process.

2.2.1 Poplar cultivation GWP emission

GWP emissions associated with poplar cultivation are applied to the poplar-production process. Table 8 summarizes the input material types and application quantities used, which are needed to estimate poplar-production emissions. Readers can find more information on farm input uses in SOM 3.

Table 8 Poplar plantation resource consumption.

Input materials	Value	Unit
Diesel use for cutting production	1.20	MJ/dry ton of poplar
Fertilizer	31.3	kg/ha
Herbicide	12.9	liter/ha
Insecticide	3.5	liter/ha
Diesel for farming activity	402.8	liter/ha
Diesel use for transport	40.1	liter/ha

To estimate the emission coefficients corresponding to our poplar field's input applications, we used the 2017 Greenhouse Gases, Regulated Emission, and Energy Use in Transportation (GREET) database developed by Argonne National Laboratory. The emission coefficients obtained for each plantation activity are shown in Table 9. It should be noted that these emissions are released in different years and are based on the frequency and timing of each activity. Therefore, we developed the LCA model in an Excel spreadsheet to keep track of the emissions on a yearly basis. We computed a carbon-emission rate of 81 g CO_2 eq/kWh using the NPV approach, accounting for the discounting factor of yearly emissions (Eq. 3).

$$Emission\ NPV = \sum_{t=0}^{n} \frac{(F)_t}{(1+r)^t} \qquad \text{Eq. 3}$$

where t denotes time period, n is maximum plant life (n=51) in this study, r is a discount factor (r=0.06%), and $(F)_t$ is a future value at time t, respectively. We first calculated NPV of total GWP emissions (during poplar production) and NPV of the total electricity produced separately. Discounting both power and emissions was necessary to obtain the total emissions per unit of power produced, because both emissions and power varied over time. Finally, the NPV of total GWPemissions was divided by NPV of the total electricity to obtain the carbon-emission rate for the power generated using the poplar biopower system, (units: g CO_2 eq/kWh).

$$Emission\ NPV\ ratio = \frac{\sum_{t=0}^{n} \frac{(GWP\ Emission)_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{(Power\ generation)_t}{(1+r)^t}} \qquad \text{Eq. 4}$$

Table 9 Poplar production emission coefficients.

	CO_2	CH_4	N_2O	CO_2 eq. total[1]	Unit
Soil preparation	420.67	0.79	0.01	443.17	kg/dry ton poplar
Establishment	54.05	0.11	0.00	57.02	kg/dry ton poplar
After planting	73.14	0.15	0.06	94.04	kg/dry ton poplar
Harvesting	78.16	0.15	0.06	99.14	kg/dry ton poplar
After harvesting	50.00	0.09	0.00	52.55	kg/dry ton poplar
Pre-harvesting	20.53	0.04	0.00	21.66	kg/dry ton poplar
Site clearance	127.68	0.28	0.00	135.28	kg/dry ton poplar

[1] CO_2 eq. are calculated using GWP of CO_2, CH_4 (GWP 25), and N_2O (GWP 298).

2.2.2 Biopower plant emissions

As the only GHG emitted from power plant operations, CO_2 emissions were expected to be 0.084 kg/MJ [11]. In our LCA model, this emission rate was also converted to the discounted total emission based on the same NPV method used to estimate the poplar emissions rate. The estimated emission rate from the biopower stationary source was 302 g CO_2 eq/kWh.

2.2.3 Poplar biogenic carbon emission

Poplar carbon sequestration emission effects were quantified in GREET for a biofuel refinery utilizing poplar feedstock [22]. We calibrated this coefficient to obtain an adjusted biogenic emissions coefficient. The two steps described below explain the calibration process in detail.

2.2.3.1 Calibrating GREET biogenic carbon emission coefficient

Based on GREET, the biogenic CO_2 equivalent of poplar plantation was -1.59 kg CO_2 eq/kWh. The technical assumptions used to generate this estimate are summarized in SOM 4. Based on these parameters, the GREET poplar biogenic emissions were converted to biogenic CO_2 eq emissions per poplar weight. In order to do so, we first calibrated the electricity generation ratio per ton of poplar biomass using boiler heat efficiency and poplar energy content, which was 1,129 kWh per dry ton of poplar. The equations used for the unit conversion process are documented in SOM 4. Using this input-output ratio, the GREET value of poplar biogenic emissions can be expressed in terms of kg CO_2 eq. per dry ton of poplar biomass. This biogenic emission is the absolute amount of CO_2 that is sequestrated per dry ton of poplar biomass. Thus, the same biogenic CO_2 emissions are expected to be present in the poplar plantations of this biopower technology. Through this calibration process, we obtained 1,795.1 (kg CO_2 eq/dry ton) as the poplar life cycle CO_2 eq emission rate (see SOM 4).

2.2.3.2 Estimating our study-specific poplar coefficient

We calculated our study's CO_2 biogenic emissions by incorporating Indiana poplar yield and power generation. The poplar plantations for this biopower system are expected to sequester 16.63 tons of CO_2 eq per ha per year (see SOM 4). Based on this emission rate, the biogenic emission was also discounted in the same manner (NPV approach) used to calculate emission rates for poplar production and power generation in the LCA model. As a result, the biogenic emission was estimated to be -1.52 g CO_2 eq/kWh.

3. Results

3.1 Techno-economic results

We developed a programming language in which stochastic simulation using an @Risk add-in [15] could interact with a Microsoft Excel macro function (see [24] for details). The simulation results, distribution of poplar sales prices, and system break-even prices, are presented in Figures 1 and 2. The mean poplar biomass price is $137.9/dry ton, with a standard deviation of $3.3/dry ton, and the mean system break-even price is 21.5 cents/kWh, with a standard deviation of 0.19 cents/kWh. This system's break-even price is approximately six times higher than the wholesale electricity price in Indiana (3.674 cents/kWh), revealing that a biopower plant of this type is not economically viable in the Indiana power market without policy intervention.

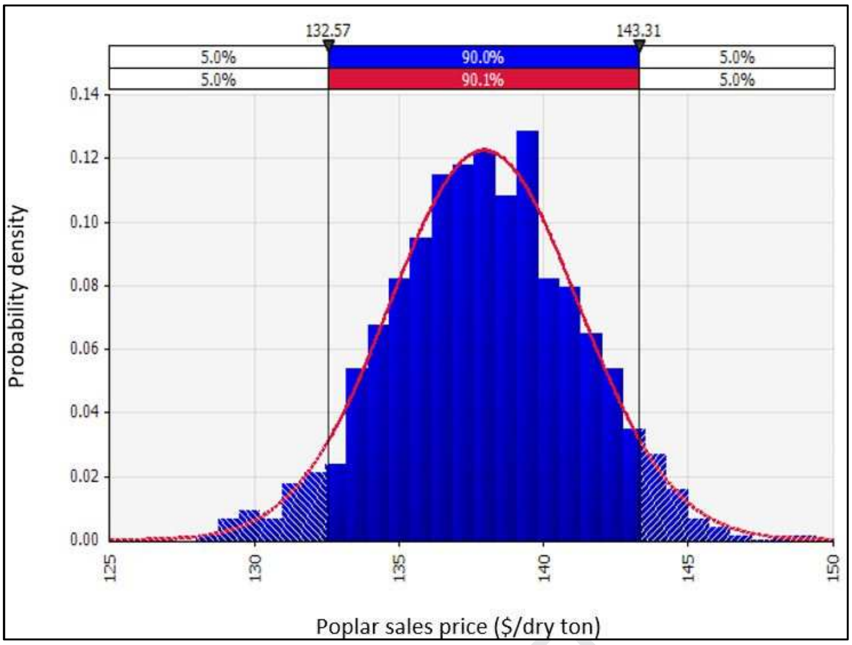

Figure 1 Poplar contract price stochastic distribution.

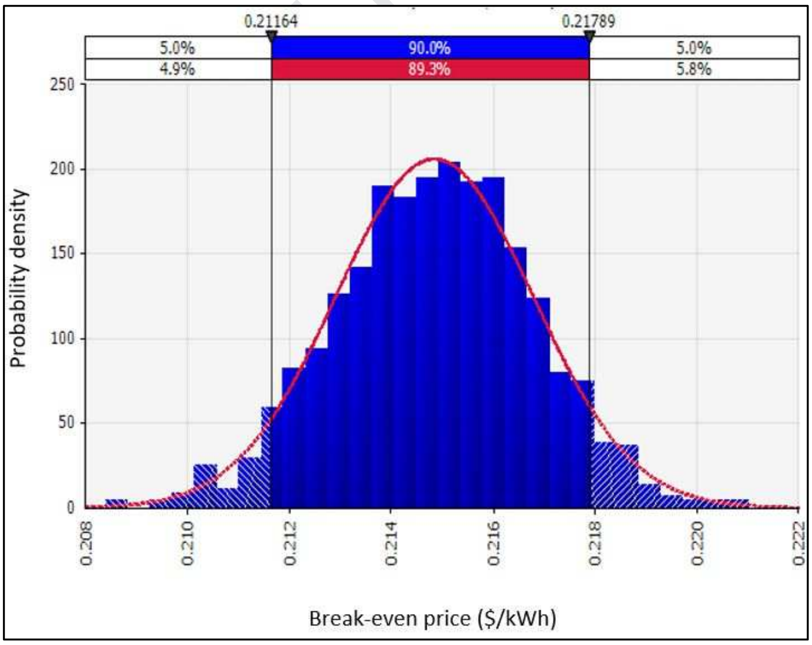

Figure 2 System breakeven price stochastic distribution

3.2 GWP emission model results

3.2.1 Net CO_2 eq. emission coefficient

The net CO_2 eq. emissions were estimated by summing all emissions from the field where poplar is grown to the stack of the power plant. Two sources of positive emissions (from the poplar planation and the power plant operation) and one source of negative emissions (the poplar's biogenic emissions) were included resulting in the expected net CO_2 eq. emissions as -1.14kg CO eq./kWh.

3.2.2 Emission analysis scenarios

In addition to this traditional LCA method, the practice of carbon neutrality was analyzed to examine a tentative renewable energy policy announced by the U.S. EPA [30]. In April 2018, the EPA declared its intent to have neutral CO_2 emissions from stationary sources using forest biomass for energy production [30]. The carbon neutrality implies that the biomass biogenic carbon emissions completely offset other emissions associated with the production and use of biomass at the power plant so that the net is zero [30]. Figure 3 compares the negative net carbon emission based on LCA analysis (-1.14 kg CO_2 eq/kWh) with zero net emissions assuming carbon neutrality.

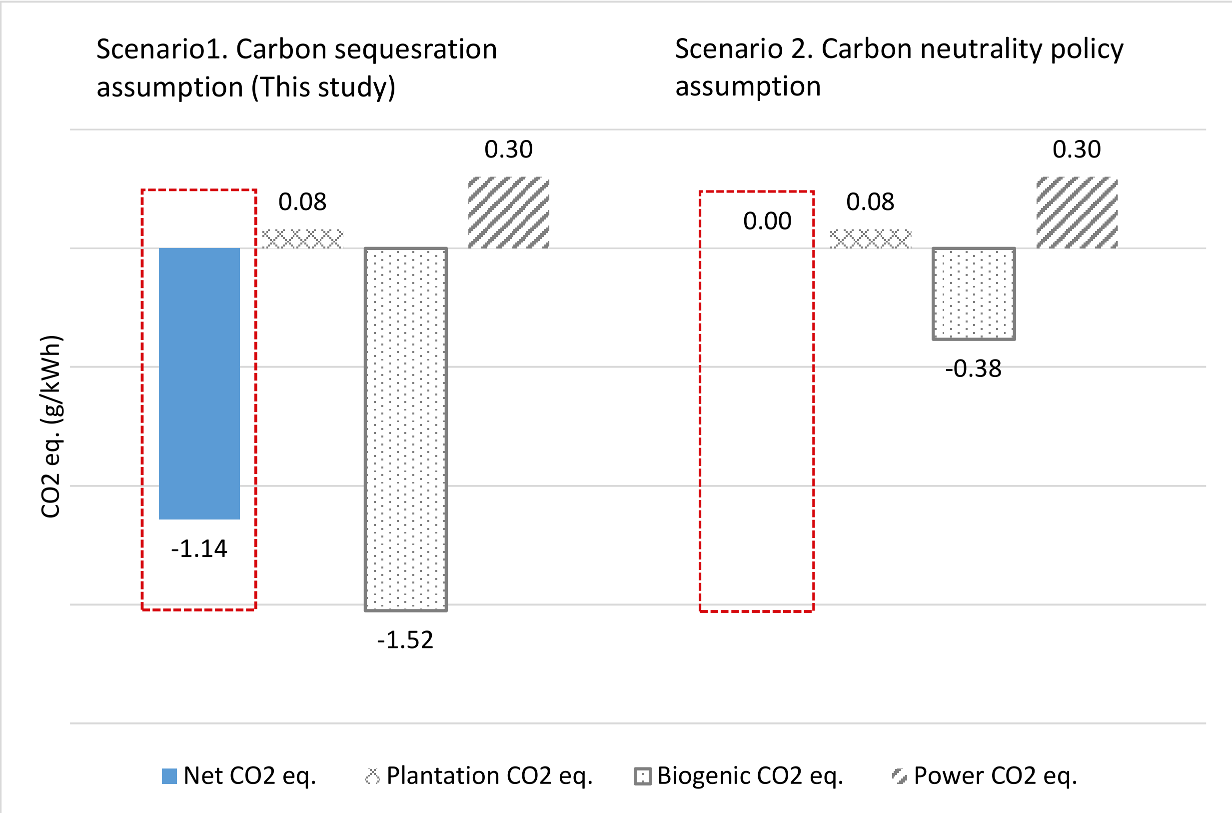

Figure 3 System net carbon emissions of two scenarios (CO2 eq. g/kWh).

3.2.2.1 Carbon tax policy

The negative net emissions of the biopower plant using SRC poplar indicates its potential as a renewable power source. However, the economic infeasibility is a significant impediment in the Indiana power market, and the pathway, therefore, requires government support in some form if it is to be commercially viable. A carbon tax can be considered to play this role because a sufficiently high price of carbon could result in this renewable power having the same economic feasibility as fossil fuel-derived power. To quantify the optimal carbon tax rate, we first assessed the current carbon emissions of the Indiana power industry.

3.2.2.2 Indiana electricity sector

For the emission assessment of the power sector, identifying heterogeneous emission rates across energy-generating units (EGU) is important because emissions from producing one kWh vary depending on the fuels types and generating technology (e.g. prime mover). In 2017, the Indiana power sector was comprised of 27 sub-categories of EGU (the combination of 15 fuel types and 9 prime mover types). Each categorized group was assigned the emission factor (g CO_2 /kWh) based on the pathway used [31]. Figure 4 illustrates the different emission rates and generation level of 2017 Indiana EGU (details are provided in SOM 6).

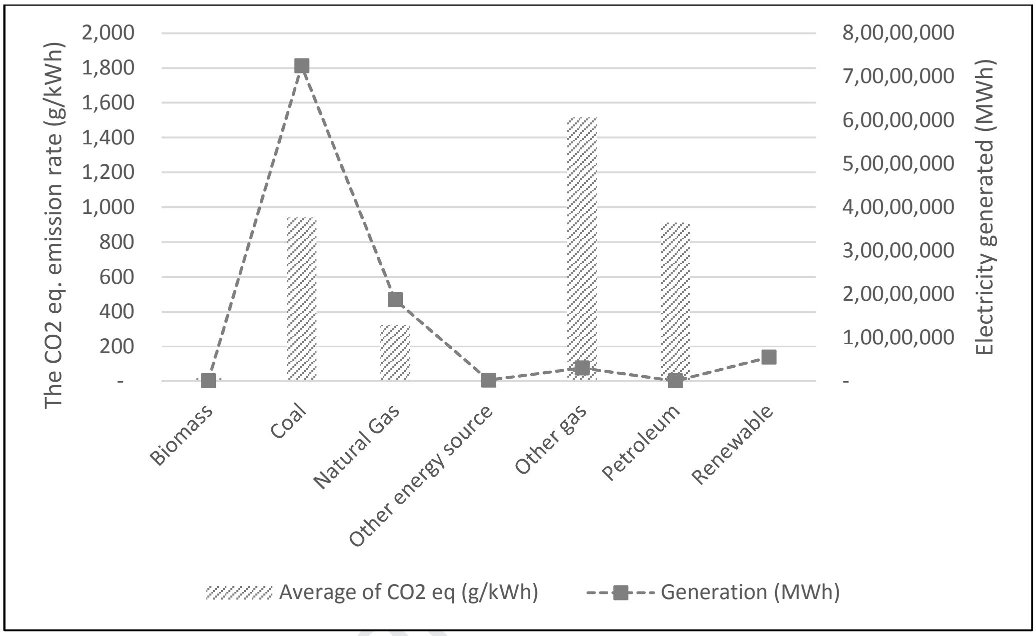

Figure 4 Emission and generation of energy generating units in Indiana (2017).

3.2.2.3 Carbon tax estimation

In an analysis of carbon tax impacts on Indiana electricity prices, we made two assumptions. First, energy substitutions in going from a carbon-intensive fuel to a less carbon-intensive fuel are not considered. Second, the total electricity generation levels in 2017 are fixed. We recognize neither of these assumptions may be valid over the long run, but power-plant configuration and demand adjustments take time, so we believe the assumptions permit an approximation of what the tax would need to be. Two consequences are expected if carbon taxes are imposed. First, the Indiana electricity price would increase, due to the carbon-emitting EGU system in Indiana. Second, the biopower plant can either lower the break-even price with the carbon tax credits (if the negative net emissions are considered) or be unaffected at all (if it is treated as carbon neutral).

To estimate the increased electricity price, we estimated the total carbon tax from each EGU in Indiana using the emissions rates and generation levels shown in Figure 4. Given the assumption that the increased fossil generation costs due to the carbon tax will all be passed on to consumers, the increments in the electricity price were calculated by aggregating the total carbon tax amounts and dividing it by the total electricity generated in Indiana. The new electricity sales price then was the addition of the current wholesale electricity price and the carbon tax-induced price increments. A higher tax implies a higher electricity price.

The appropriate carbon tax can be found at the intersection where the line representing the biopower system can break-even price crosses the new wholesale electricity price (Figure 5). If the poplar biopower plant is treated as a carbon sink, based on its negative emissions, a carbon tax of \$93.5/ton CO_2 eq makes this system economically feasible. However, if the biopower plant is treated as carbon neutral, a much higher carbon tax (\$213.4/ton CO_2 eq) is required.

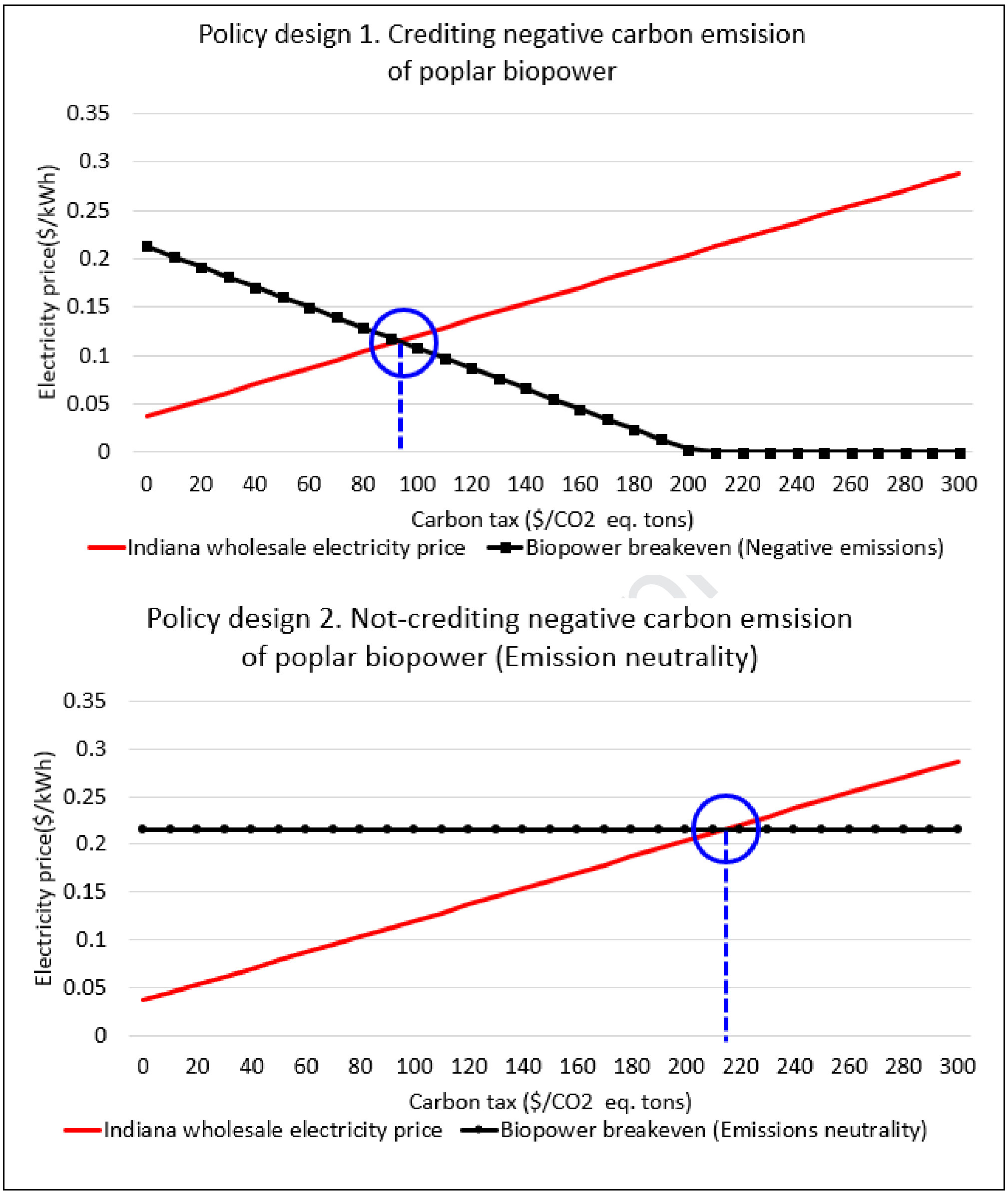

Figure 5 Carbon tax making biopower plant feasible.

3.2.2.4 The implication of the estimated carbon tax

There are many studies that have quantified a carbon tax, but they show large variability in the carbon tax price, depending on the study assumptions and methods. For example, an interagency working group of the U.S. government quantified the social carbon costs of $45 per ton CO_2 eq by accounting for its monetized damages [32]. In other studies, much higher carbon taxes were estimated to be needed to achieve some environmental goals. For example, a carbon tax of $150/ton CO_2 eq would be needed to meet the 50% emissions reduction target of the Paris

Accord[33]. Kim et al. found that the carbon tax up to \$375/ton CO_2 eq would be required to achieve a 550-ppmv emission scenario [34] and \$160/ton CO_2 eq tax is estimated for reducing GHG emissions and increasing energy security [35]. Given the various carbon valuations, the biopower plant project's viability will depend upon the carbon tax rate chosen by policymakers. It will be feasible only if the carbon tax is imposed above what is estimated for this biopower plant.

4. Discussion

4.1 Sensitivity analysis

The large scale of the plantation for this system implies a high likelihood of variable land quality. To explore the sensitivity of the analysis result to different land types, we defined three types of land, based on productivity and rent cost: excellent, average, and poor land. The yield data employed in this study (average land) was used to approximate the yield of excellent and poor land yield based on the coefficient of variance from [18]. Table 10 shows that the low yield of poor land required larger land area than excellent land to produce the same amount of biomass, but the rent for the poor land was cheaper [36]. For the stochastic analysis, a PERT distribution was used for the yield of excellent and poor land similar to the stochastic analysis of average land in section 2.1.4 (see SOM 7).

Table 10 The mean of poplar yield of three land types.

	Yield mean	Needed land area	Land costs
Excellent land	43.71 dry ton/ha	4,968 ha	\$593/ha
Average land	27.79 dry ton/ha	7,815 ha	\$330/ha
Poor land	18.97 dry ton/ha	11,448 ha	\$67/ha

From the Monte-Carlo simulation, the mean and standard deviation of system break-even price was 20.2 cents/kWh and 0.26 cents/kWh for poor land, 21.5 cents/kWh and 0.19 cents/kWh for average land, and 20.4 cents/kWh and 0.12 cents/kWh for excellent land. Our t-test results suggest that these all were statistically different at a 95% confidence level. As expected, the poor land has the largest standard deviation, whereas excellent land has the smallest (Figure 6). In other words, higher risks will be attached to the poor land and lower risks for the excellent land. Although the mean break-even price was the lowest using poor land, the comparison of break-even price itself must be of limited value because the land-rent data were only estimates. With different rent value, the ranks can always vary. Thus, the differences are statistically significant, but not economically significant.

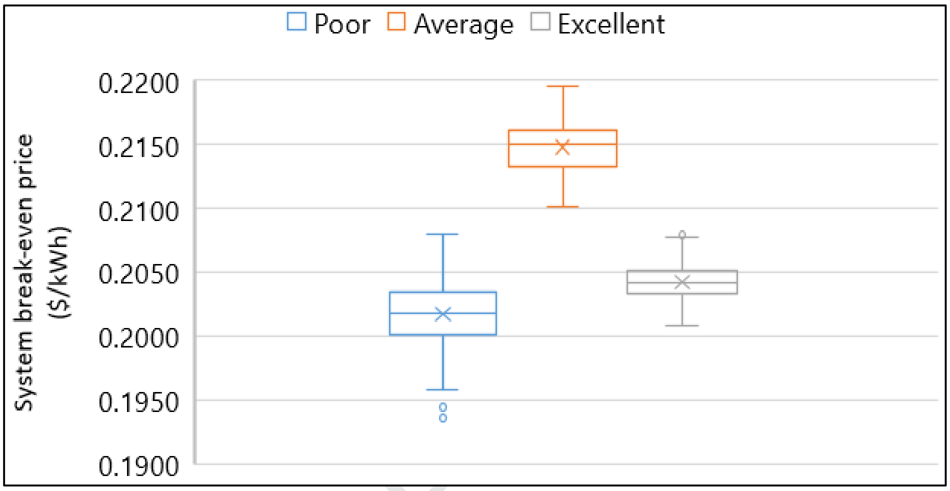

Figure 6 System break-even price distribution of land types.

4.2 The sensitivity of carbon effects

The GHG-reduction effect of the same biopower plant pathway can vary, depending on the planting circumstances, because the life cycle net emissions will depend on the initial soil carbon stock. If poplar trees are planted on land which was previously a high carbon sink (e.g. grassland), the biopower plant's emission reduction effect is smaller than if the land had low soil organic carbon stocks (e.g. cropland). Figure 7 illustrates this biopower plant's environmental effect in comparison with two contrasting cases (case 1: grassland and coal-power plant, and case 2: cropland and coal-power plant). The soil organic accumulation rate of grassland (332 kg/ha/year) and cropland (200 kg/ha/year) were used as a proxy of biogenic emissions for each land type by referring to [37] and [38], respectively. The SRC poplar biopower plant had a greater GHG reduction effect relative to either fossil-energy alternative.

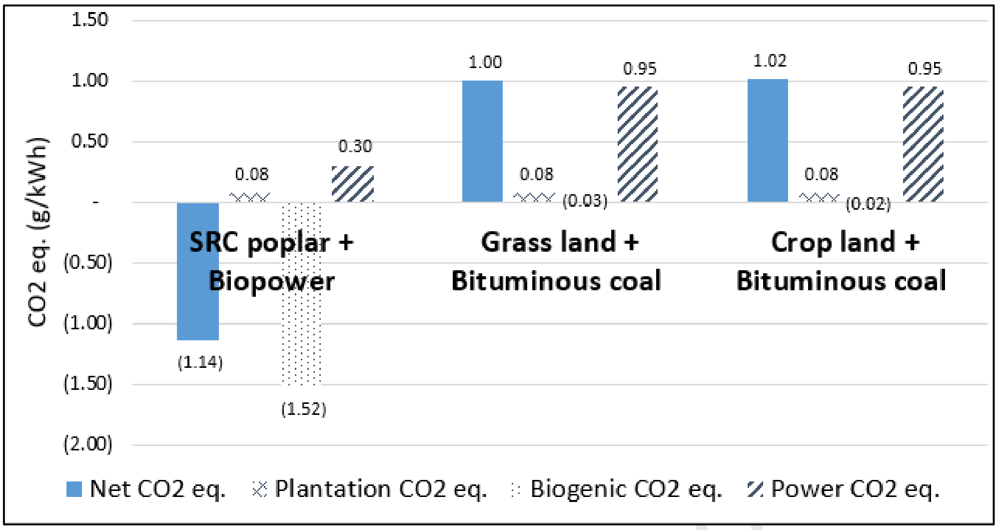

Figure 7 Environmental effect sensitivity analysis

In Indiana, low-value land is usually pastured grassland, whereas high-value land is used for growing crops. Given this land-use pattern, we expect higher soil organic carbon stocks in the poor land than for excellent land. Therefore, using excellent land for poplar plantations is expected to have higher environmental benefits than poor land. In conjunction with our finding that excellent land mitigates the risks, high GHG-reduction effects can also be expected when using excellent land.

5. Conclusions

As the availability of a reliable source of feedstock appears to be the key element for the successful biopower plant operation, SRC poplar is gaining attention as promising choice, due to its rapid growth, but there exist policy-driven debates over whether a biopower plant should be considered to be a renewable source of energy. In other words, it is still uncertain whether a biopower plantwould reduce or increase net carbon emissions, hence the need for LCA analysis of a system that includes biomass production. This work attempted to answer these questions by presenting the economic feasibility and CO_2 eq. emission-reduction potential of an SRC poplar-fueled biopower pathway in Indiana.

We found two pieces of evidence to support the conclusion that poplar biopower plant operation in Indiana is untenable. First, biopower plant is not economically feasible in the current Indiana power market because the estimated system break-even price (21.5 cents/kWh) is approximately six times higher than the Indiana wholesale electricity price (3.67 cents/kWh). The main contributions to the high break-even price are the high upfront capital costs of biopower plant and biomass purchase costs (for details, see SOM 5). Although ownership of property for SRC poplar plantations helps to reduce biomass production costs by avoiding repeated field set-ups and replanting costs following harvest, biomass purchase costs are still the most costly expenses to a power generating plant. In addition, it may be infeasible to rely on poplar biomass as a feedstock for generating power in Indiana because vast acreage is needed to provide sufficient feedstock for a biopower plant. As a result, the land resource is likely to be a considerable limitation when using a biopower plant to substitute for a coal-fired power plant. In addition, this land-use change is not likely to occur because farmers tend to adhere to the conventional farming practices with which they are most familiar. The land required for biopower plants to substitute for the nine coal-fired plants currently operating in southern Indiana (12,474 MW) would be 5,273,827 ha, which is equivalent to 89% of the total agricultural crop land available in Indiana.

Based on our LCA analysis, using an Indiana-based SRC poplar biopower plant as a renewable source of electricity would reduce GHG emissions substantially, compared to power plants dependent on fossil-fuels. Accordingly, this investment could be attractive from an environmental perspective. Although our economic findings have led us to conclude that a biopower plant is not realistic in Indiana, we see the potential of this system with a stringent environmental policy target. With a carbon tax above \$93.5/ton CO_2 eq, the biopower plant would be viable in Indiana. However, such a high carbon tax will only be implemented under an aggressive GHG emission-reduction target such as the one specified in the Paris Accord. If this were done, a biopower plant could be competitive with other renewable-energy technologies in Indiana. Compared to the most popular renewable energy sources in Indiana—wind and solar—biopower generation is expected to be less sensitive to weather[1]. In other words, a reliable uninterrupted renewable power source has higher value because its grid-integration costs are much lower. However, further analysis by comparing poplar-based power with interruptible wind and solar power is beyond the scope of this study.

[1] For this reason, biopower plant has a higher capacity factor than other renewable power plant (Biomass including wood:55.6%, conventional hydropower : 38.2%, wind: 34.5%, solar photovoltaic: 25.1%) [39]

Finally, it is clear that carbon-policy design will greatly affect the economic feasibility of this system. If carbon policy accounts for the carbon sequestration effect of SRC poplar plantations, a carbon tax could be as low as \$93.5/ton CO_2. However, if the policy applies a uniform zero-emission rule to a biopower pathway, regardless of feedstock type, then a much higher carbon tax (\$213.4/ton CO_2) would be required to make a poplar-fed power plant economically competitive with the current fossil fuel-based electricity generation. We do not anticipate any unintended economic impacts resulting from a high carbon tax, as proposed above; however, further study is needed to explore the social welfare effects of an electricity price change that could be driven by a carbon tax.

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Highlights:

- A SRC poplar fed Biopower plant is economically infeasible in Indiana.
- With a carbon tax ($93.5/ton CO2 eq), it can be competitive in Indiana.
- Large land area needed for poplar plantations impedes project viability.
- Carbon sequestration leads to net emissions of -1.14 kg CO2 eq/kWh.
- Slight over-producing biomass (0.83%) leads to the most favorable system economics.