An Optimization Model in Support of Biomass Co-Firing in Coal Fired Power Plants

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Outline

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Motivation

Co-firing biomass is an attractive renewable energy option:

- Increases renewable energy without major capital investments and investments in the infrastructure
- Low risk option
- Reduces emissions of CO_2, SO_2 and NO_2 emissions
  - 5% (15%) co-firing would reduce CO_2 emissions by 5.4% (18.2%)
- Minimizes waste - such as, wood waste, agricultural waste - and the environmental problem associated with waste disposal
- It is a near term market solution for biomass

Motivation

Renewable electricity generation is expected to increase due to the following reasons (EIA):

- Increasing demand for electricity
- Programs encouraging renewable energy use (e.g. PTC, RPS etc.)
  - PTC: An income tax credit of 2.3 cents/kilowatt-hour
- The implementation of new environmental rules dampens future coal use (e.g. Cross-State Air Pollution Rule of EPA)

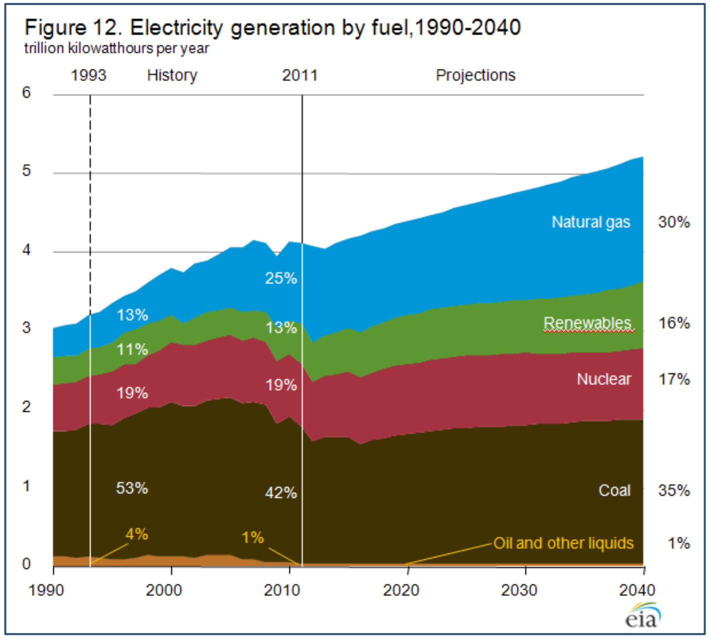
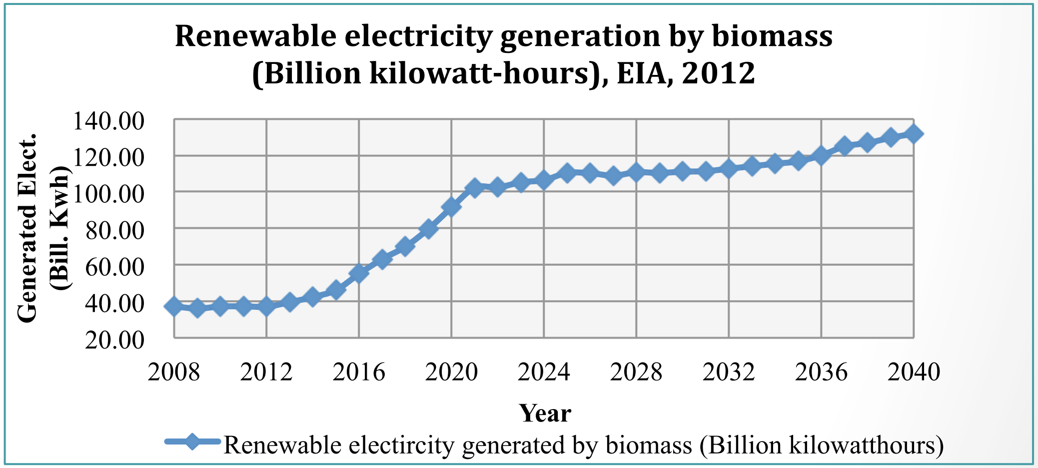


Figure 12. Electricity generation by fuel,1990-2040



Renewable electricity generation by biomass (Billion kilowatt-hours), EIA, 2012

Literature review

- Currently, 40 of 560 coal-fired power plants in USA co-fire biomass.

- Two major barriers for adopting co-firing are:
  - Additional plant investment costs
  - High cost of biomass transportation and inventory holding

- The literature is mainly focused on analyzing its technological and economical feasibility.

- There are no studies which integrate logistics and investment decisions in coal-fired power plants.

Research Objectives

- Develop an optimization model in support of biomass co-firing decisions in coal-fired power plants.

  The model captures the:
  - Additional costs and savings
  - Loss of process efficiencies due to co-firing

- Evaluate the impact of Production Tax Credit (PTC) on renewable electricity production.

A Non-Linear Optimization Model

Decision variables

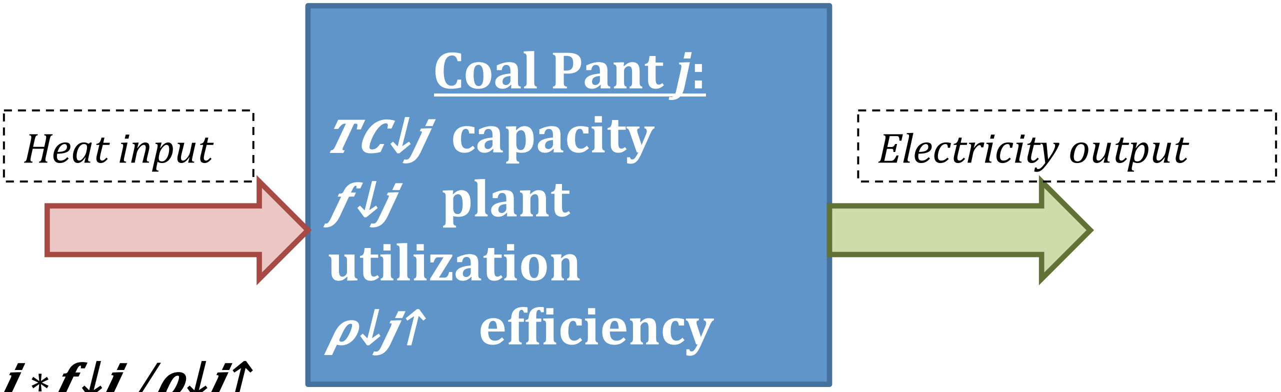
- $\boldsymbol{X_{ij}}$ the amount of biomass (in tons/year) delivered to coal plant *j* from supplier *i*

    Amount of biomass needed at plant *j* is: $\sum_{i\in S} X_{ij}$

- $\boldsymbol{B_j}$ the percentage of coal displaced in plant *j*
- $\boldsymbol{Y_j}$ binary variable which takes the value 1 if $B_j \leq 4\%$ and takes the value 0 otherwise

Model Formulation

Modeling of plant efficiency loss due to co-firing [1].



Heat input

Coal Pant *j*:

TC_j capacity

f_j plant utilization

ρ_j efficiency

Electricity output

$$Q_j = TC_j * f_j / \rho_j$$

$$M_j^{coal} = Q_j * OH_j * C^{wb} / LHV_j^{coal}$$

Model Formulation cont.

Biomass has a lower heating value than coal. Let ΔM_j^{coal} be the amount of coal displaced.

Energy balance equation: $LHV_j^{bm} * \sum_{i \in S} X_{ij} = LHV_j^{coal} * \Delta M_j^{coal}$

The amount of biomass required is:

$$\sum_{i \in S} X_{ij} = \Delta M_j^{coal} \, LHV_j^{coal} / LHV_j^{bm}$$

The efficiency loss of boilers when biomass is used (Tillman 2000):

$$EL_j = 0.0044 * B_j^2 + 0.0055$$

$$\sum_{i \in S} X_{ij} = \Delta M_j^{coal} * LHV_j^{coal} / LHV_j^{bm} * \rho_j^b / \rho_j^b - EL_j$$

Problem Description

Plant investment costs

- If the percentage of coal displaced is $B_j \le 4\%$, capital investment $\$50/\mathrm{KW}_{bm}$ (Caputo et al. 2005):

$$I_j^{CAP} = 50{,}000 * M_j^{bm} / M_j^{coal} - \Delta M_j^{coal}\ TC_j * f_j * LHV_j^{bm} / LHV_j^{coal} =$$

$$50{,}000 * TC_j * f_j * LHV_j^{bm} / LHV_j^{coal} * B_j / 1 - B_j = \boldsymbol{I_j^{cap} (B_j / 1 - B_j)}$$

- If $B_j > 4\%$, new investments required:

Biomass storage: $I_j^{S} = 136578 * (TC_j * f_j * LHV_j^{bm} / LHV_j^{coal} * B_j / 1 - B_j)^{0.5575} = \boldsymbol{I_j^{s} * (B_j / 1 - B_j)^{0.5575}}$

Biomass handling: $I_j^{H} = 55780 * (TC_j * f_j * LHV_j^{bm} / LHV_j^{coal} * B_j / 1 - B_j)^{0.9554} = \boldsymbol{I_j^{h} * (B_j / 1 - B_j)^{0.9554}}$

Compressors and driers: $I_j^{CD} = 13646 * (TC_j * f_j * LHV_j^{bm} / LHV_j^{coal} * B_j / 1 - B_j)^{0.5575} = \boldsymbol{I_j^{CD} * (B_j / 1 - B_j)^{0.5575}}$

Problem Description

Operating costs

Biomass market price $/ton

- Biomass purchase cost: $\sum_{i \in S} c_i^{bm} X_{ij}$
- Transportation cost: $\sum_{i \in S} c_{ij} X_{ij}$

Unit transporting cost from supplier i to plant j

Savings

- Coal displacement

  $S_j^p = c_j^{coal} * \Delta M_j^{coal} = \sigma_j^p * \sum_{i \in S} X_{ij}$

Coal market price $/ton

- Production Tax Credit (PTC): 2.3 cents/KWh$_{bm}$

  $S_j^{tax} = 23 * LHV_j^{bm} / C^{wb} * M_j^{bm} = \sigma_j^t * \sum_{i \in S} X_{ij}$

A Non-Linear Optimization Model

Objective function

- $Maximize: Z = \sum_{j \in C} \left((\sigma_j^p + \sigma_j^t) \sum_{i \in S} X_{ij} \right)$

$$- \sum_{i \in S, j \in C} (c_{ij}^t + c_i^{bm}) X_{ij}$$

$$- \sum_{j \in C} (I_j^s + I_j^{cd})(1 - Y_j)(B_j / 1 - B_j)^{0.5575}$$

$$- \sum_{j \in C} I_j^h (1 - Y_j)(B_j / 1 - B_j)^{0.9554}$$

$$- \sum_{j \in C} I_j^{cap} (B_j / 1 - B_j) Y_j$$

Savings due to coal displacement and PTC

Biomass procurement and transportation costs

Storage and compressor-drier costs for $B_j > 4$

Handling costs for $B_j > 4$

Capital investments costs for $B_j \leq 4$

A Non-Linear Optimization Model

Constraints

Subject to:

$$\sum_{j \in C} X_{ij} \le s_i \qquad \text{for all } i \in S \qquad (1)$$

$$\sum_{i \in S} X_{ij} \le (Q_j^0 * OH_j * C^{wb} * \rho_j^b)/LHV_j^{coal}/(1/B_j - \alpha_j) * (\rho_j^b - 0.0044 B_j^2 - 0.0055) \qquad \text{for all } j \in C \qquad (2)$$

$$B_j - 0.04 \le M(1 - Y_j) \qquad \text{for all } j \in C \qquad (3)$$

$$0.04 - B_j < MY_j \qquad \text{for all } j \in C \qquad (4)$$

$$X_{ij} \in R^+ \qquad \text{for all } i \in S, j \in C \qquad (5)$$

$$B_j \in [0, 1] \qquad \text{for all } j \in C \qquad (6)$$

$$Y_j \in \{0, 1\} \qquad \text{for all } j \in C \qquad (7)$$

A Linear Optimization Model

Consider plant j could displace coal (by mass) either at a rate of $B_j = 1\%$, or 2%, or 3%, etc.

Let $l = 1, \ldots, |L|$ index the set of all potential values that B_j can take. L_l denote the l–the element of this set

Decision variables:

Y_{lj} binary variable which takes the value 1 if facility j *displaces* $L_l = B_j\,\%$ coal, and takes the value 0 otherwise

X_{ij} the amount of biomass (in tons/year) delivered to coal plant j from supplier i

A Linear Optimization Model

For a fixed value of $\boldsymbol{B_j}$:

$\sum_{i\in S} X_{ij} \le (Q_j^0 * OH_j * C^{wb} * \rho_j^b)/LHV_j^{coal}/(1/B_j - \alpha_j)*(\rho_j^b - 0.0044B_j^2 - 0.0055)$ (2)

$M_{lj}^{bm} = (Q_j^0 * OH_j * C^{wb} * \rho_j^b)/LHV_j^{coal}/(1/B_j - \alpha_j)*(\rho_j^b - 0.0044B_j^2 - 0.0055)$ is a constant.

$\sum_{i\in S} X_{ij} \le \sum_{l\in L} M_{lj}^{bm} Y_{lj}$ for all $j\in C$ (2*)

$I_{lj} = \boldsymbol{I_j^{cap}(B_j/(1-B_j))}$ is a constant.

$\sum_{j\in C} \sum_{l\in L} I_{lj} Y_{lj}$

A Linear Optimization Model

- $Maximize: Z = \sum_{j\in C} \left((\sigma_j^p + \sigma_j^t) \sum_{i\in S} X_{ij} \right)$

$$- \sum_{i\in S, j\in C} (c_{ij}^t + c_i^{bm}) X_{ij}$$

$$- \sum_{j\in C} \sum_{l\in L} I_{lj} Y_{lj}$$

Savings due to coal displacement and PTC

Biomass procurement and transportation costs

Investment costs

Subject to:

$\sum_{j\in C} X_{ij} \le s_i$ for all $i\in S$ (1)

$\sum_{i\in S} X_{ij} \le \sum_{l\in L} M_{lj}^{bm} Y_{lj}$ for all $j\in C$ (2*)

$\sum_{l\in L} Y_{lj} \le 1$ for all $j\in C$ (8)

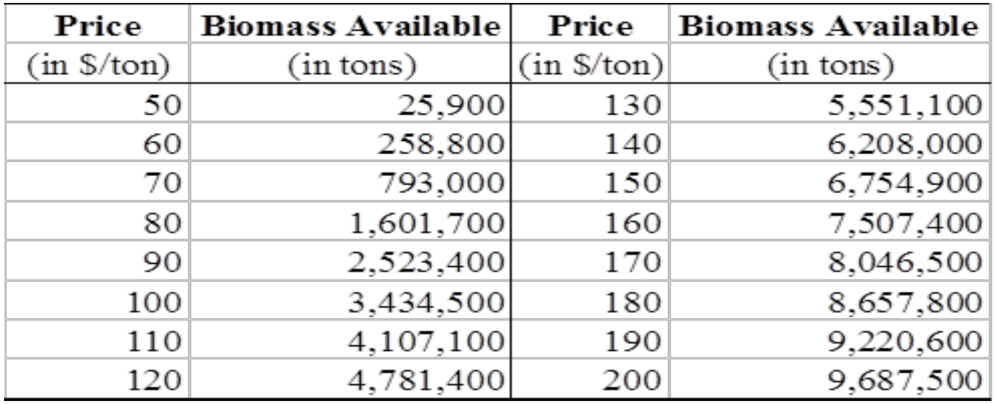
$X_{ij} \in R^+$ for all $i\in S$, $j\in C$ (5)

$Y_{lj} \in \{0, 1\}$ for all $l\in L, j\in C$ (9)

A Case Study

Biomass supply in the state of Mississippi [4]:

- Knowledge Discovery Framework (KDF)
- Woody biomass; available for different price targets



Price (in $/ton)	Biomass Available (in tons)	Price (in $/ton)	Biomass Available (in tons)
50	25,900	130	5,551,100
60	258,800	140	6,208,000
70	793,000	150	6,754,900
80	1,601,700	160	7,507,400
90	2,523,400	170	8,046,500
100	3,434,500	180	8,657,800
110	4,107,100	190	9,220,600
120	4,781,400	200	9,687,500

Truck transportation [5]:

- Distance fixed cost (DFC): $3.01/(tons)
- Distance variable cost (DVC): $0.112/(tons mile)
- $c_{ij}^{t} = DFC + DV * d_{ij}$

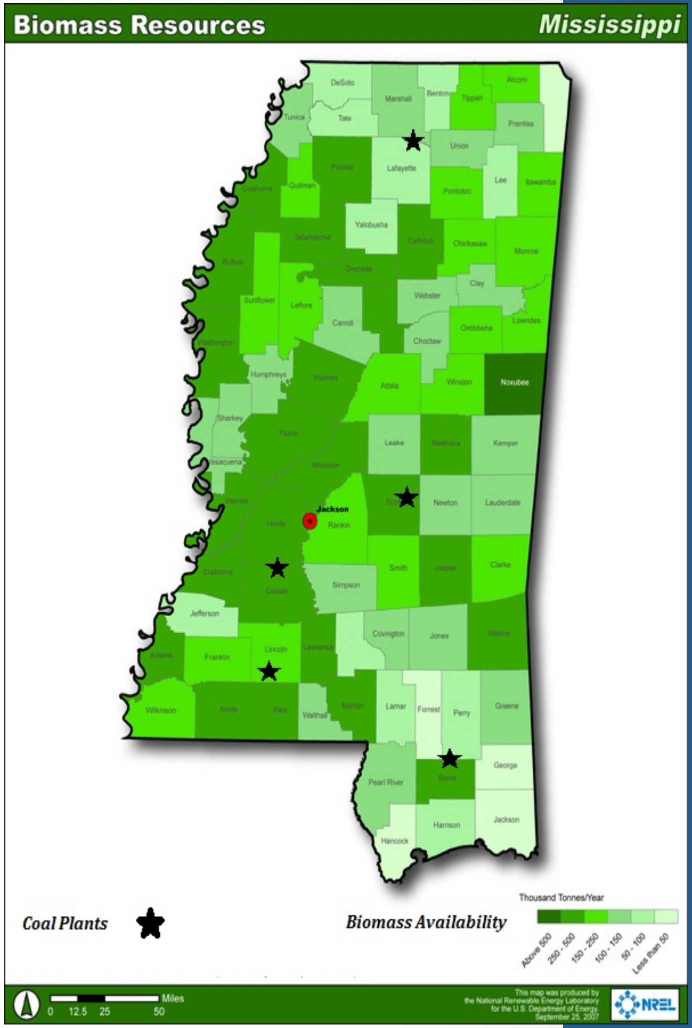
A Case Study

Coal plants data [6]:

- National Energy Technology Laboratory
- Power plants of capacity greater than 1MW

Plant Name	*Primary Fuel*	*Fuel Type*	*Nameplate Capacity (MW)*	*Capacity Factor*
Red Hills	COAL	Lignite coal	514	0.7213
Henderson	COAL	Bituminous coal	59	0.1078
R D Morrow	COAL	Bituminous coal	400	0.7281
Victor J Daniel Jr	COAL	Bituminous coal	2,229	0.4986
Jack Watson	COAL	Bituminous coal	1,216	0.3544

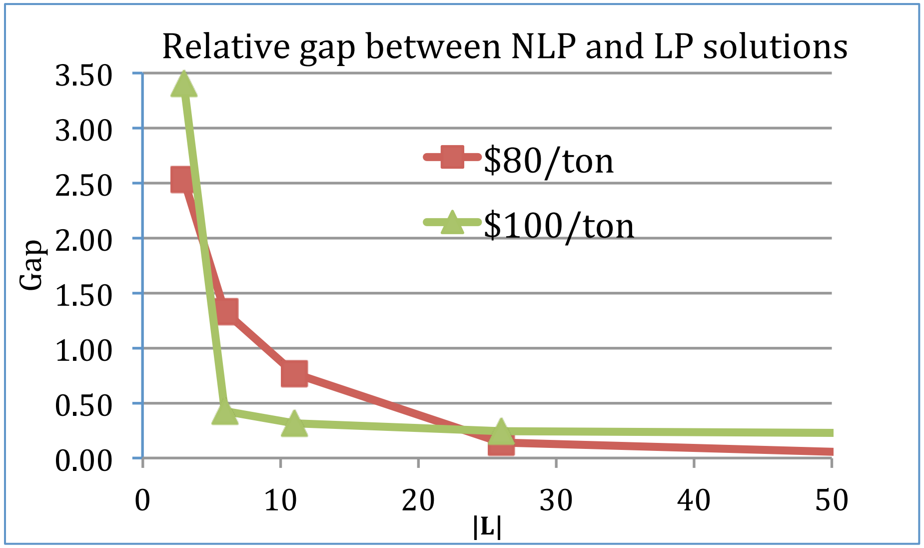
Product	**LHV (BTU/ Ton)**
Woody biomass	16,811,000
Bituminous coal	22,460,600
Lignite coal	19,536,300



Numerical Results

Solved using GAMS and BONMIN, CPLEX on a personal computer.

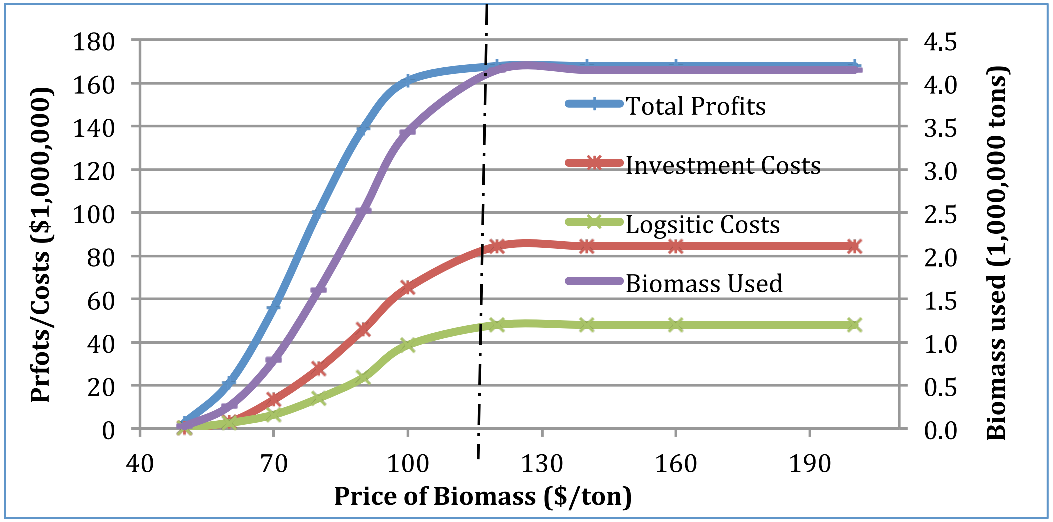
- It took a few seconds to solve all the problem instances.



Relationship between the size of set $|L|$ and the quality of solutions of LP formulation.

- Increasing the size of $|L|$ impacts the quality of the solutions found from LP formulation.

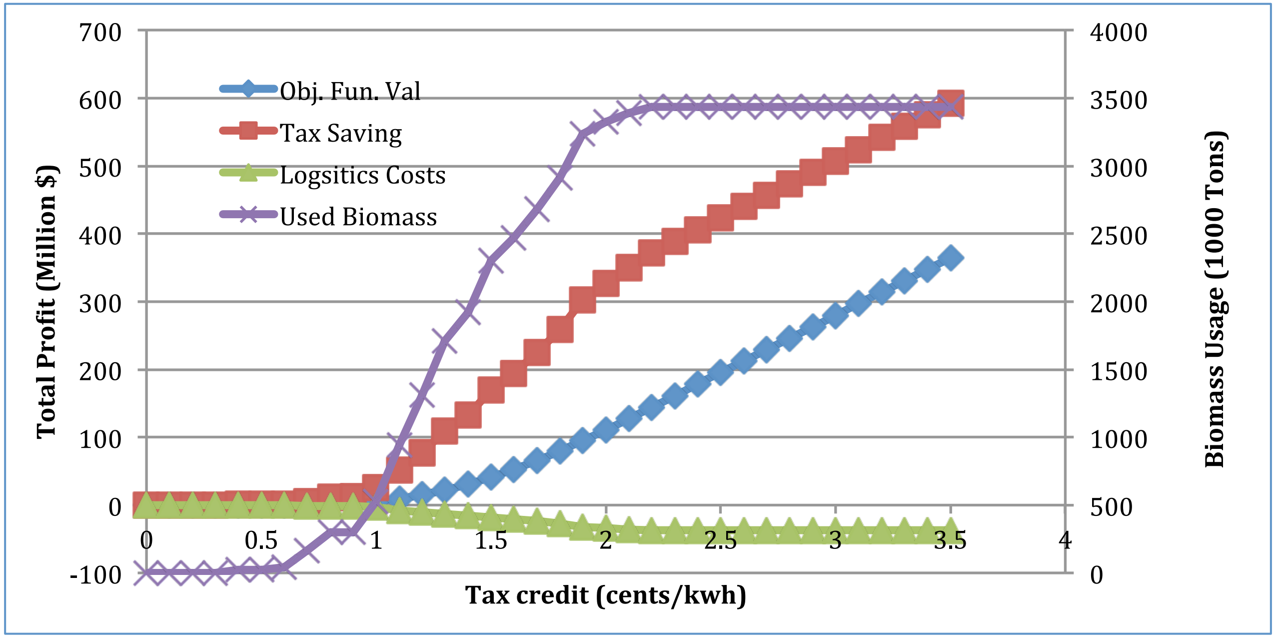
Numerical Results



Relationship between biomass price, investment costs, logistics costs, profits, biomass use.

- Increasing the target price of biomass for a fixed PTC of 2.3cents /kwh :
  - **Market price ≤ $120/ton**:
    - **Profits increase** since savings from PTC are greater than the additional costs from investment and transportation
    - Renewable electricity production increases.
  - **Market price > $120/ton:**
    - Renewable electricity production remains constant.

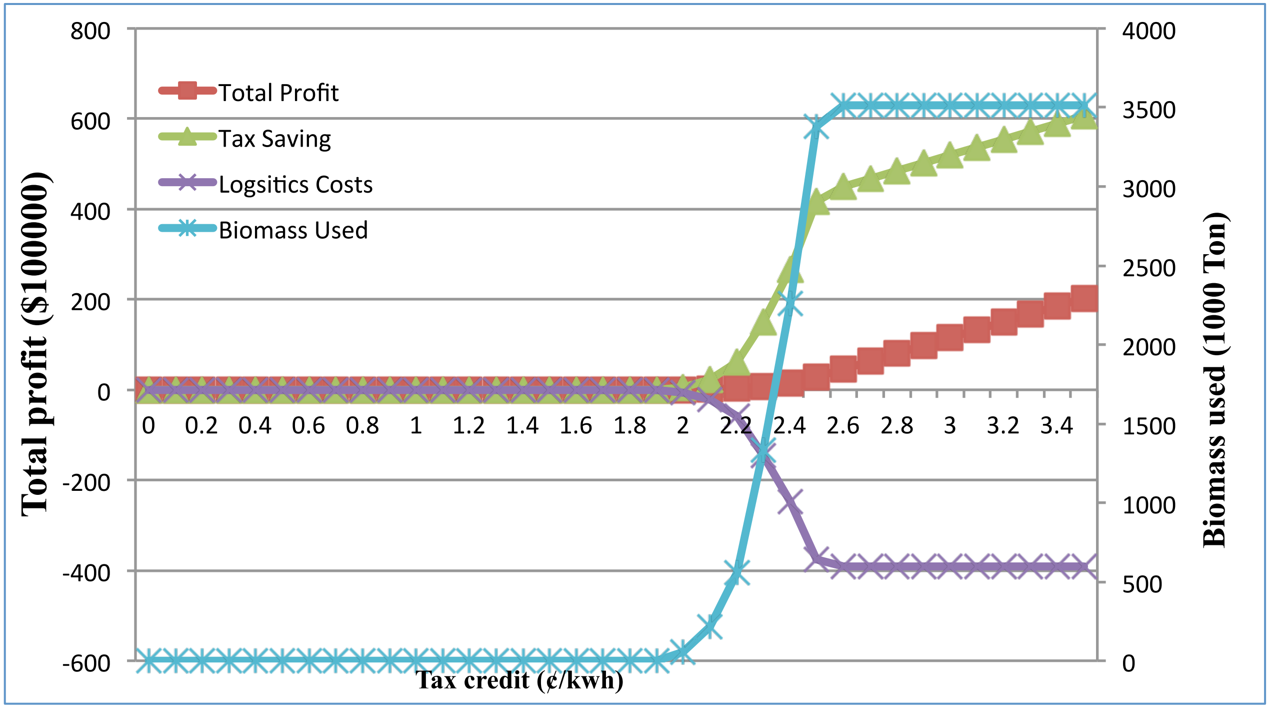
Numerical Results



The impact of tax credits on profits and biomass usage for biomass **target price of $100/ton**

- **In Mississippi**: Cofiring not profitable for PTC ≤**0.7** cents/kwh
- For PTC ≥ **2.2**
  - Renewable electricity production does not increase
  - Profits continue increasing

Numerical Results



The impact of tax credits on profits and biomass usage for biomass **target price of $100/ton**

- **South Carolina**: Cofiring not profitable for PTC ≤**2.1** cents/kwh
- For PTC ≥ **2.6**
  - Renewable electricity production does not increase
  - Profits continue increasing

Summary of findings

- Tax credits necessary to increase the production of the renewable energy.
- Tax credit should not be "one size fits all". PTC could be a function of the amount of renewable electricity produced.
- Biomass availability in the USA differs by region. To optimize renewable energy production, the tax rate should be customized by region.

Current Research

Develop solution algorithms to solve the LP approximation model:

- $Maximize: Z = \sum_{j \in C} \left((\sigma_j^p + \sigma_j^t) \sum_{i \in S} X_{ij} \right) - \sum_{i \in S, j \in C} (c_{ij}^t + c_i^{bm}) X_{ij} - \sum_{j \in C} \sum_{l \in L} I_{lj} Y_{lj}$

Subject to:

$\sum_{j \in C} X_{ij} \le s_i$ for all $i \in S$ (1)

$\sum_{i \in S} X_{ij} \le \sum_{l \in L} M_{lj}^{bm} Y_{lj}$ for all $j \in C$ (2*)

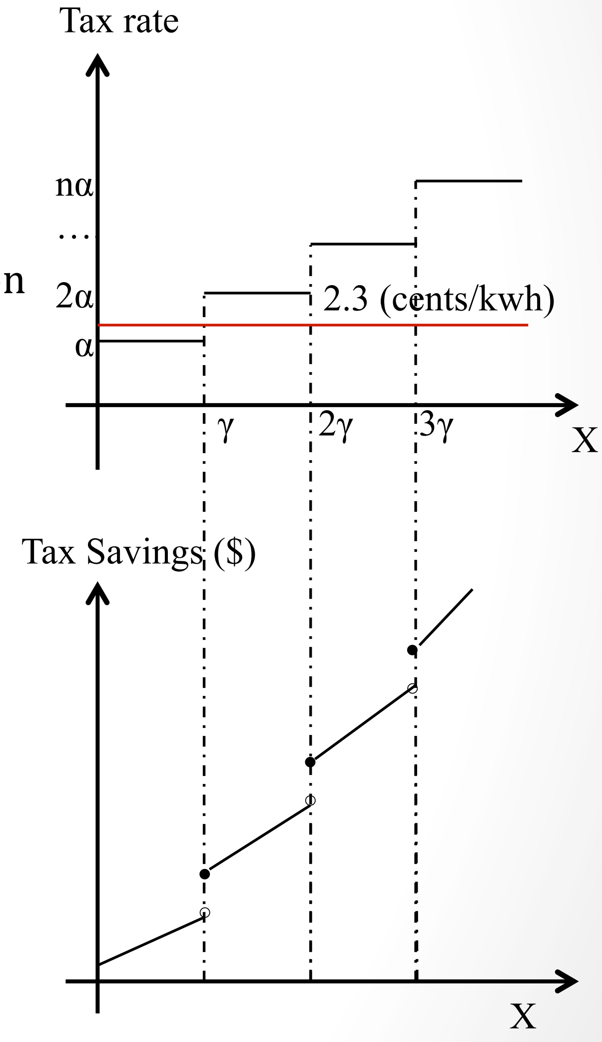
$\sum_{l \in L} Y_{lj} \le 1$ for all $j \in C$ (8)

$X_{ij} \in R^+$ for all $i \in S, j \in C$ (5)

$Y_{lj} \in \{0, 1\}$ for all $l \in L, j \in C$ (9)

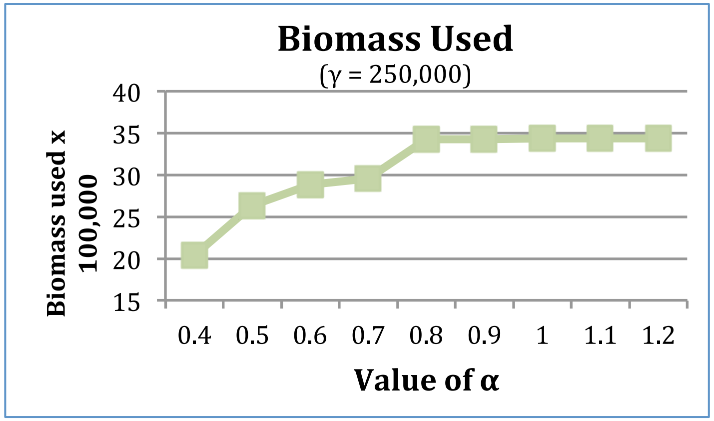
Current Research

- Investigate the impact of tax schemes on renewable electricity production:
  - Tax rate as a function of biomass usage
  - Tax rate as a function of plant capacity
  - Tax rate as a function of biomass available in the region



- Initial results:

The unit PTC is smaller than 2.3/kwh


Biomass Used

(γ = 250,000)

Future Research

- Consider supply chains that span larger regions. In this case the in-bound supply chain will have a hub-and-spoke structure.

- Develop models which optimize costs and the social impacts of co-firing:
  - Use a Stackelberg game model:
    - Leader: Decision makers at the federal level that identify a PTC structure
    - Followers: Coal plants that decide on the amount of coal to displace.
    - The goal is to a PTC which optimizes the social benefits without sacrificing power plants profits.

Questions?

References

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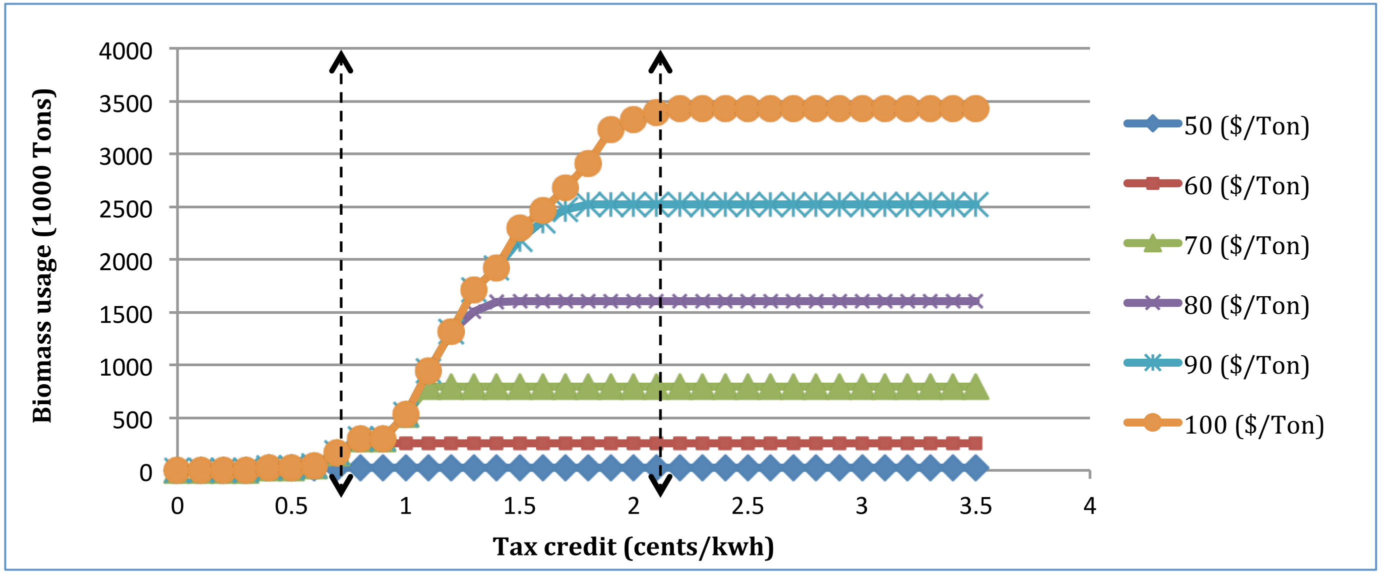
Numerical Results



The impact of tax credit and targeted price on biomass usage.

- Tax credits are necessary for production of the renewable energy
  - For Mississippi, cents 0.7/kwh is a lower bound on PTC
- Increasing PTC impacts positively the amount of renewable energy produced
  - At $100/ton: When PTC is less than cents 2.1/kwh, only some of the available biomass is used

Current Research

Develop solution algorithms to solve the LP approximation model:

- $Maximize: Z = \sum_{j\in C} \left((\sigma_j^p + \sigma_j^t) \sum_{i\in S} X_{ij} \right) - \sum_{i\in S, j\in C} (c_{ij}^t + c_i^{bm}) X_{ij}$
  $- \sum_{j\in C} \sum_{l\in L} I_{lj} Y_{lj}$

Complicating constraints:

Subject to:

$\sum_{j\in C} X_{ij} \le s_i$ for all $i\in S$ (1)

$\sum_{i\in S} X_{ij} \le \sum_{l\in L} M_{lj}^{bm} Y_{lj}$ for all $j\in C$ (2*)

$\sum_{l\in L} Y_{lj} \le 1$ for all $j\in C$ (8)

$X_{ij} \in R^+$ for all $i\in S$, $j\in C$ (5)

$Y_{lj} \in \{0, 1\}$ for all $l\in L, j\in C$ (9)

Current Research

Lagrangean relaxation model:

$$Max: Z^{\lambda} = \sum_{i\in S, j\in C} \blacksquare\, C_{ij} X_{ij} - \sum_{j\in C} \sum_{l\in L} I_{lj} Y_{lj} + \sum_{i\in S} (s_i - \blacksquare\, C_{ij} X_{ij})\, \lambda_i$$

Subject to:

$\sum_{i\in S} X_{ij} \le \sum_{l\in L} M_{lj}^{bm} Y_{lj}$ for all $j\in C$ (2*)

$\sum_{l\in L} Y_{lj} \le 1$ for all $j\in C$ (8)

$X_{ij} \in R^{+}$ for all $i\in S$, $j\in C$ (5)

$Y_{lj} \in \{0, 1\}$ for all $l\in L, j\in C$ (9)

Current Research

For a give facility *j* and a given set of multipliers λ_i:

$$Max: Z^{j\lambda} = \sum_{i\in S} (C_{ij} - \lambda_i) X_{ij} - \sum_{j\in C} \sum_{l\in L} I_{lj} Y_{lj}$$

Subject to:

$\sum_{i\in S} X_{ij} \le \sum_{l\in L} M_{lj}^{bm} Y_{lj}$ (2)

$\sum_{l\in L} Y_{lj} \le 1$ (8)

$X_{ij} \in R^+$ for $i\in S$ (5)

$Y_{lj} \in \{0,1\}$ for $l\in L$ (9)

Theorem: The LP-relaxation of this problem provides the optimal solution.

Lemma: In an optimal solution to this problem plants receive shipments from a single supplier.

Current Research

The dual of Lagrangean relaxation model can easily be solved using a simple inspection procedure:

$$If: \max_i \{0, C_{ij} - \lambda_i\} = C_{i*j} - \lambda_{i*} > 0,\ then:$$

$$■ If: \max\{0, \max_l \{M_{lj}(C_{i*j} - \lambda_{i*}) - I_{lj}\}\} = M_{l*j}(C_{i*j} - \lambda_{i*}) - I_{l*j} > 0,\ then:$$

$$Y_{l*j} = 1;\ Y_{lj} = 0\ for\ l \in L/\{l^*\}$$

$$X_{i*j} = M_{lj};\ X_{ij} = 0\ for\ i \in I/\{i^*\}$$

We are working on fine tuning the algorithm.