# A Model for the Economic Evaluation of Plantation Biomass Production for Co-firing with Coal in Electricity Production

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Public and private electric utilities are considering co-firing biomass with coal as a strategy to reduce the levels of $CO_2$, $SO_2$ and $NO_x$ in stack emissions, as well as a response to state legislative mandates requiring the use of renewable fuels. This analysis examines the conditions under which biomass co-firing is economically feasible for utilities and woody biomass producers and describes additional environmental and community benefits associated with biomass use. This paper presents a case study of woody biomass production and co-firing at the Northern Indiana Public Service Company (NIPSCO) Michigan City Unit No. 12 power plant. A *Salix* (willow) production budget was created to assess the feasibility of plantation tree production to supply biomass to the utility for fuel blending. A GAMS model was developed to examine the optimal co-firing blend of coal and biomass while minimizing variable cost, including the cost of ash disposal and material procurement costs. The model is constrained by the levels of pollution produced. This model is used to examine situations where coal is the primary fuel and waste wood, willow trees, or both are available for fuel blending. Capital costs for co-firing were estimated outside of the model and are incorporated into the total cost of co-firing. The results indicate that under certain circumstances it is cost-effective for the power plant to co-fire biomass. Sensitivity analysis is used to test biomass price sensitivity and explores the effects of potential public policies on co-firing.

Scientists agree that a buildup of greenhouse gasses in the earth's atmosphere, primarily carbon dioxide ($CO_2$), is contributing to a gradual increase of the earth's temperature (Associated Press 1998). In addition to carbon emissions, the production of gaseous sulfur and nitrogen oxides from the burning of fossil fuels can lead to the acidification of soils, rivers, and bodies of water. This acid pollution can damage plants and buildings as well as soils and waterways. Also these gasses may enhance the natural greenhouse effect, causing increased global mean temperatures, changes in vegetation zones, and increased global mean sea level. These potential environmental impacts have prompted environmentalists, government officials, and the general public to call for changes in production systems for utilities and other industrial sectors. While energy production raises environmental concerns, its production also is linked to national security, development and economic growth issues (Gustavsson, Borjesson, Johansson and Svenningsson 1995). Therefore, utilities, governments, and environmental groups are searching for clean ways to produce electricity.

In response to the Clean Air Act Amendments of 1990, public utilities have embarked on programs to reduce the amounts of $CO_2$, $SO_2$, and $NO_x$ in stack emissions (Moore 1996; ORNL 1995). One way emissions could be reduced is through co-firing biomass with coal to produce electricity (Hohenstein and Wright 1994). Biomass, defined as a renewable energy resource of organic non-fossil material, constitutes anything from refuse wood material or crop residues to herbaceous and woody crops grown specifically to be burned with fossil fuels (Moore 1996).

Biomass produces less $CO_2$, $NO_x$, and $SO_2$ in stack emissions (World Coal 1996), saving utili-

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ties' sulfur emission allowances. Sulfur permits, each of which allow a utility to emit one ton of sulfur in the form of $SO_2$, trade for about $90 each and this indicates that there could be a cost savings potential with biomass use (World Coal 1996). When burned, biomass produces less ash than coal, providing the power plant with savings on waste disposal (EPRI 1995a). Biomass production can reduce the amount of waste routed to landfills while stimulating rural economies with increased crop revenues (DOE 1996). Co-firing biomass is also an efficient way for society to reduce the level of greenhouse gasses in the atmosphere (Gustavsson et al. 1995). Utilizing biomass instead of fossil fuels in electricity and heat production is generally less costly and provides larger $CO_2$ reductions per unit of biomass than substituting biomass for gasoline or diesel fuel used in motor vehicles (Gustavsson et al. 1995).

Use of biomass in electricity production can offer additional benefits. The Electric Power Research Institute (EPRI) estimates that biomass production could represent a new agricultural market worth as much as $12 billion a year in the U.S. farm-sector economy (Moore 1996). In addition, utilities can strengthen relationships with industrial customers by utilizing their solid and liquid organic wastes either directly as fuel or as fertilizer for biomass crops (EPRI 1995a).

Although utilities are interested in co-firing programs with biomass, they are unsure how to start these programs and what costs they may face (Moore 1996; DOE 1996). This paper presents the costs associated with woody biomass production, transportation, and use in northern Indiana and discusses the potential for a local utility, the Northern Indiana Public Service Company (NIPSCO), to co-fire biomass with coal in a cyclone burner in Michigan City, Indiana. Sensitivity analysis is used to examine biomass price sensitivity and the effect of increased environmental regulation and government policies on co-firing efficacy.

## Background

Using biomass to produce energy is not a new idea. Almost all power came from wood combustion until the late 19th century (Zerbe 1988b). Fossil fuels (coal, oil, and gas) became the primary sources of energy because they were inexpensive, readily accessible, and offered high Btu (British thermal units) content (Hohenstein and Wright 1994). Biomass fuel use diminished between 1870 to 1970 as fossil fuel consumption rose. The declining importance of biomass energy was first re-examined in 1973 with the OPEC oil embargo and again in 1979 after the Iranian revolution (Zerbe 1988b).

In the late-70s, gas and oil price increases and availability concerns prompted the Department of Energy (DOE) to start biomass research. DOE viewed biomass as a viable alternative to fossil fuels and focused on strategies to implement renewable fuel use (Hohenstein and Wright 1994). To encourage the use of biomass in energy production, Congress passed the 1978 Public Utility Regulatory Policies Act, which provided incentives for co-generation and small power production facilities (Moore 1996). As a result, the grid generating capacity fueled by biomass increased from 200 MW to over 7000 MW by 1995 (Moore 1996). However, the major groups using biomass as a fuel source were forest products industries which generated wood waste as a byproduct, not utilities (Zerbe 1988a).

Although the fuel shortages foreseen in the 1970s have not materialized, environmental concerns associated with fossil fuel use have prompted re-examination of alternative fuels (Hohenstein and Wright 1994). The revived interest in biomass fuels on environmental grounds has led to increased federal support (Moore 1996). The 1992 Energy Policy Act encouraged the use of bio-fuels by providing a tax credit of $0.015 per kilowatt-hour of electricity generated from biomass (closed-loop) systems which sequester $CO_2$ during the plant growth cycle (Moore 1996). In 1993, the Department of Energy co-funded feasibility studies for ten different biomass programs around the country to assess the commercial viability and environmental considerations of a variety of biomass systems in different locations. The Department of Energy is seeking industry partners interested in conducting demonstration projects with these energy crops (DOE 1996).

Power plants produce more than a third of the country's annual nitrogen dioxide ($NO_2$) and greenhouse gas emissions. They also provide about three-quarters of the sulfur dioxide ($SO_2$) emissions in the United States (Burtraw, Krupnick, and Palmer 1996). The benefit utilities derive from co-firing biomass fuel in existing boilers is a reduction in sulfur dioxide emissions. In addition, the use of biomass fuels may yield greater-than proportional reductions in emissions of nitrogen oxides (Moore 1996), a pollutant recently targeted by the U.S. EPA for strict reductions from Midwestern power plants. When used in power generation, biomass also will displace significant amounts of fossil resources and thus help minimize increases in atmospheric carbon dioxide (Turnbull 1994).

Secondary factors influencing the use of renewable energy are state policies promoting renewable energy (DOE 1996). Minnesota, for example, has mandated that the Northern States Power Company have 125 MW of biomass-fired generation under contract by 2002 (Moore 1996). Mandates like Minnesota's can drive utilities' development of renewable energy resources. The development of renewable energy resources will be necessary to comply with future pressure from international environmental efforts, like the recently agreed to Kyoto Protocol (EIA 1998).

Biomass resources include wood wastes and residues from the production of paper and wood products, agricultural residues, traditional tree plantations, forest thinnings, landfill wastes, and specialized herbaceous and wood crops developed specifically for energy production (Hohenstein and Wright 1994). Woody biomass represents 81% of the total biomass resource (DOE 1996).

Urban wood wastes, construction/demolition wood waste, and materials from land clearing are also potential sources of biomass. However, these forms of wood are not recommended for energy production because they are difficult to quantify, can be highly variable in quality, and may be available in limited quantity (EPRI 1995b). Logging residues, whole-tree chipping operations, and primary (wood and bark from pulp- and papermills, sawmills, and panel mills) and secondary (furniture, crafts) wood processing residues are more practical wood resources (EPRI 1995b). These resources can be co-fired alone with coal or as part of a mixture with a dedicated energy crop.

Characteristics that can make logging residues, whole-tree chips, and processed wood resources hard to utilize in power generation include a high moisture content (typically 50% or higher), irregular particle sizes and dimensions, and the presence of foreign materials, including metals (Foster Wheeler 1996). An additional consideration for these resources is stable availability. Since the 1970s these resources have been used by the forest products industries to produce energy or value-added products (Zerbe 1988b). The State of Wisconsin, for instance, found that 65% of all mill residues were already being converted to energy (Wisconsin Energy Bureau 1994).

The utility industry is reluctant to build power plants fired by nontraditional fuels for which supply systems are not fully developed (Zerbe 1988b). For this reason, the Department of Energy's goal for future biomass energy is to have a steady supply of biomass available for electricity generation. This will be accomplished through the use of Dedicated Feedstock Supply Systems (DFSS).

Unlike most biomass programs where a low value co-product like alfalfa stems are gathered and used as fuel, DFSS crops are cultivated solely to be used in energy generation. Widespread DFSS production will lower the cost of producing energy crops and provide a steady stream of biomass. By 2016 the Department of Energy would like to be able to achieve 17,000 MW of additional biomass power capacity. This goal would require planting 5.5 million acres of dedicated energy crops in the next 20 years (DOE 1996).

Wright (1994) has identified four major categories of plant species that are being considered for dedicated biomass production based on their rapid growth, wide site adaptability, pest resistance, and disease resistance. Species groups being considered are thin-stemmed perennial; thick-stemmed perennial; annuals; and woody species. Of these, woody biomass is ideal for electricity generation because it converts to thermal energy and gasification more efficiently than herbaceous energy crops (Hohenstein and Wright 1994). Wood feedstocks have lower moisture content, lower ash, and higher energy values per ton than herbaceous biomass. Other desirable attributes include less crop loss in storage and infrequent soil disturbance for establishment and harvest (Hohenstein and Wright 1994).

Dedicated woody crops offer benefits to power generation companies and producers over other sources of woody biomass (EPRI 1995b). DFSS is a fuel dedicated to power generation and is unlikely to have a higher value elsewhere in wood using industries. DFSS is also a long-term sustainable fuel source largely immune to land-use regulations and is therefore a reliable resource. Tree production can be located near energy conversion plants, reducing transportation costs (EPRI 1995b). Markets for woody biomass already exist for paper and pulp products, and this could make the transition from traditional agriculture to energy crops less risky (Hohenstein and Wright 1994).

A variety of species have been considered, including poplar (*Populus* spp.), sycamore (*Platanus occidentalis* L.), eucalyptus (*Eucalyptus* spp.), silver maple (*Acer saccharinum* L.), and willow (*Salix* spp.). Some species like eucalyptus, however, can only be grown in Hawaii, Florida, and parts of California, making them unsuitable for widespread use (Wright 1994). Poplars have been the most widely tested trees for Short-Rotation Intensive Culture (SRIC) in the North Central region of the U.S. They are the first choice of many growers because they are extremely fast growing (Meridian Corporation 1986). In experimental trials, poplar has achieved yields between 20 to 43 Mg $ha^{-1}$ $yr^{-1}$ (Wright 1994).

Hughes and Wiltsee (1997) have standardized the costs of supplying biomass from four different studies to include processing and transportation costs for comparison purposes. The results from the three studies using poplar hybrids are as follows. The Pennsylvania State University School of Forest Resources has estimated the cost of supplying biomass from poplar at $53.39 per dry ton. This is equivalent to $3.14 per MBtu. However, this work was based on data and assumptions that are now somewhat dated (Hughes and Wiltsee 1997). The Oak Ridge National Laboratory (1995) estimated the delivered fuel costs for poplar at $66.62 per dry ton or $3.92 per MBtu. The Natural Resources Research Institute at the University of Minnesota has done research on poplar plantations for the upper Midwest and estimated hybrid poplar production costs at $62.53 per dry ton or $3.68 per MBtu (Bergson 1994). With a producer subsidy in the form of an additional federal CRP land rent payment, these costs are reduced to $45.19 and $2.66, respectively (Hughes and Wiltsee 1997). In comparison, natural gas costs electric utilities $1.25 to $2.25 per MBtu and coal costs $0.90 to $1.35 per MBtu (Moore 1996).

Attention is now being focused on willow (*Salix* spp.) as the species of choice for energy plantations. There are several reasons why willow is a preferred energy crop. Willow is easily planted using non-rooted cuttings and it can sprout repeatedly from stumps (Meridian Corporation 1986). Like poplar, it sprouts vigorously, grows rapidly, and yields large quantities of biomass. Willow trees will reach heights of 20–30 ft in three years and are harvested on a 3–5 year rotation (Volk 1997a). By comparison, most poplar plantations have growth cycles between 5–8 years (Hughes and Wiltsee 1997). Since the hybrid willow is so good at regenerating, the original plants can live for about 6 cycles or 18 years before new cuttings would have to be planted (Sandoval 1997). They grow particularly well on wet or poorly drained sites or on peatland and this characteristic makes them an ideal crop for marginal croplands (Meridian Corporation 1986).

Research in New York has found that willow crops can produce 11.2–17.9 dry Mg $ha^{-1}$ $yr^{-1}$ on a commercial scale (Volk 1997a). Biomass yields up to 30 dry Mg $ha^{-1}$ $yr^{-1}$ have been achieved with present commercial *Salix* clones with optimized fertilization combined with irrigation. This is equal to 13.4 dry tons of biomass per acre (Borjesson 1996).

Little breeding work has been done with willows so there is great potential for developing improved varieties (Volk 1997a). Weed control, clonal adaptation, and better disease resistance are examples of measures that may be taken to increase yields of short-rotation forests. In research plots, for example, yield increases of 35 to 40% have been achieved in Sweden using new *Salix* clones originating from Siberia, mainly due to their higher resistance to frost and rust fungi (Borjesson 1996). An important additional advantage for the use of willow is the ease with which it can be harvested. Instead of employing large, commercial tree harvesters, willow shrubs can be harvested with a modified combine, similar to those used to harvest corn (Robison, Abrahamson, White, and Volk 1996).

An accurate cost estimate for willow production in the United States is provided by Dr. Edwin White and his colleagues at the State University of New York (SUNY), College of Environmental Science and Forestry. Hughes and Wiltsee (1997) modified this data and concluded that the delivered fuel cost for willow is $36.46 per dry ton or $2.14/MBtu. This figure is lower than the three estimates for poplar production provided above (Hughes and Wiltsee 1997). This information suggests that willow may be the preferred species for energy production based strictly on financial criteria.

## The Michigan City Case Study

The Northern Indiana Public Service Company (NIPSCO), a subsidiary company of NIPSCO Industries, Inc., is an energy based, investor-owned holding company. NIPSCO is a private, tax-paying utility serving a 12,000 square mile area in the northern one third of Indiana. With a customer base of more than 2.2 million people, NIPSCO is the largest gas-distribution company and the second largest electric-distribution company in Indiana.

NIPSCO became interested in co-firing wood waste with coal after utilities like Northern States Power (NSP) successfully commercialized this technology at King Station (Foster Wheeler 1996). In 1996, NIPSCO commissioned a feasibility study from the Foster Wheeler Environmental Corporation to examine co-firing urban wood waste in one of three candidate coal-fired cyclone boilers. Foster Wheeler identified the primary issues that have motivated NIPSCO to consider co-firing with wood. They are:

> NIPSCO, like other utilities, is facing the uncertainty of a deregulated industry. Co-firing can incrementally reduce fuel costs, and support economic development

> of customers by offsetting waste disposal costs while maintaining customer loads.
>
> NIPSCO will voluntarily comply with targets set under the global climate challenge agreement and is seeking low cost methods to reduce greenhouse gas emissions.
>
> NIPSCO faces the proposed U.S. Environmental Protection Agency rule concerning acid rain and the proposed limit of 0.94 lb. $NO_x/10^6$ Btu of fuel input. Co-firing is proven to reduce $NO_x$ emissions in cyclone boilers.

Since this study, additional market factors are providing incentives for NIPSCO to develop co-firing potential. These include the request of NIPSCO, by utilities in neighboring states for any "green" or environmentally produced power to supply market needs and state regulatory requirements. These requests have shown NIPSCO the importance of this growing niche market. But these requests also foreshadow the regulatory environment that may impact power generation in Indiana.

In August 1996, Foster Wheeler Environmental Consultants identified the Michigan City Unit No. 12 as the most promising cyclone boiler for co-firing and developed a facility plan. Two reasons for the selection of the Michigan City power plant as a feasible co-firing site were the availability of wood wastes in the area around the plant and the layout of the fuel yard, which would enable the installation of a biomass fuel system adjacent to the main conveyor belt. In addition, the staff at this unit has demonstrated experience in handling and firing alternate materials and the wood co-firing could have significant beneficial combustion and pollution control impacts at the Michigan City location.

In the spring of 1997, NIPSCO conducted an experimental test burn at the site to determine what difficulties may be associated with co-firing. Important results of this test burn were that although boiler temperatures were slightly lower with 10% by volume biomass co-firing, boiler efficiency and flyash quality were maintained. $NO_x$ emissions were reduced by 9.5% and $SO_2$ emissions were lowered by 6.9%. Carbon dioxide output was reduced by 26.7 tons per hours (Foster and Wheeler 1997).

## The Michigan City Power Plant

The Michigan City Unit No. 12 was installed in 1974 with a capacity of 469 $MW_e$. The unit is a supercritical boiler with a single reheat loop. A blend of 60% Black Thunder (Powder River Basin) coals and 40% Shoshone coal is burned. With this 60/40 blend, the plant has an emission rate of 0.95 to 0.98 lb. $NO_x$/MBtu of fuel input. This rate is close to the proposed EPA standard of 0.94 lb. $NO_x$/MBtu of fuel input (Foster Wheeler 1996).

The only air pollution control system used at this plant is an electrostatic precipitator (ESP). The ESP was rebuilt in 1992 and has 24 fields (Foster Wheeler 1996). In 1998 this plant was granted 17,317 pollution permits to emit sulfur dioxide ($SO_2$) (EPA 1998). One ton of sulfur dioxide may be released into the atmosphere for every permit held by the power plant. Additional permits may be bought on a national market. This year, sulfur dioxide permits sell for about $68 (EPA 1998).

The plant fires 25 tons/cyclone-hour when operating at full capacity. Coal is discharged from the bunkers through stock feeders and into the radial feeders of the cyclones. Each cyclone is 10 feet in inside diameter. Shoshone coal causes fouling, but this can be controlled by proper blending with PRB coal. Slag trapping also has been a problem, particularly when firing low loads with blends having high concentrations of PRB coals. Slag trapping problems limit the low load to 280 $MW_e$ (Foster Wheeler 1996).

To assess the financial viability of co-firing woody biomass at the Michigan City power plant, three different options were considered. The first method was co-firing plantation-grown willow alone with coal. The second was co-firing a blend of plantation-grown willow and $2.00/ton waste wood with coal. The third option examined co-firing the waste wood and willow blend with coal when the waste wood had a higher per ton price of $15.00.

The rate of return on investment was calculated with an initial investment of $100,000 for the 1997 co-firing test burn and a one-time capital expenditure of $1,163,000 in the following year. This is followed by 22 years of co-firing in which additional expenses for taxes, maintenance costs and expenditures on wood are measured against the savings on fewer pollution permits, lower coal expenditures, and reduced ash disposal costs. The rate of return on investment for the willow and $2.00/ton waste wood blend 55%. The co-firing blend of $15.00/ton waste wood and willow has a slightly lower return of 52%. Co-firing with willow alone with coal did not recover the initial investment costs and had a negative rate of return.

## Biomass Production

The first method of providing the power plant with woody biomass is through the production of *Salix* trees in the surrounding area. Transporting energy crops is expensive and biomass power plants are likely to be located within 50 miles of where the feedstocks are grown (Moore 1996). Since it is not felt that biomass crops can be directly competitive with traditional row crops in this area, we estimated the amount of available, lower priced pastureland within this region. The total number of non-wooded pastureland acres for each county can be found in the 1992 U.S. Census of Agriculture. This acreage must then be divided by the approximate percent of the county with appropriate soil types for *Salix* production to provide a rough acreage estimate. For counties that have only a portion of land in the selected area, it is assumed pastureland is evenly distributed across the county.

The estimated number of acres available in Indiana for biomass production within the 50-mile radius from Michigan City is 6,960, concentrated in Marshall, St. Joseph, and Starke counties. In the first 10-mile radius around Michigan City we have assumed that there are 400 acres of pastureland available (5% of the total), in a 30-mile radius this number will increase to 2565 acres or 37% of the total pastureland. At a 50-mile radius the entire 6,960 acres of pastureland (100% of the total) are available for willow production.

Willow cropping systems are based on traditional agricultural practices and have been modified to capitalize on the natural characteristics of this species. The Biomass-Bioenergy program at the State University of New York's College of Environmental Science and Forestry has had over 15 years of experience with willow production. Since willow production in northern Indiana is similar to production in New York, this production system and the corresponding budget are based largely on the Biomass-Bioenergy program's research.

Willows achieve best growth with unrestricted water availability (Hughes and Wiltsee 1997). With irrigation, willow clone SV1 has yielded 22.4 dry Mg $ha^{-1}$ $yr^{-1}$ (10 dry tons/acre/year) (EPRI 1995b). Yet, economic analysis of irrigation has shown it to be clearly unattractive because of the high costs of purchasing and operating the required equipment. Irrigation is, therefore, not recommended for most SRWC plantations (Meridian Corporation 1986). A more commercially attractive means of supplementing nutrients and water in certain situations is through the application of wastewaters and sludges. Materials that may be suitable for application include biosolids, waste gypsum, wood ash, some pulp and paper sludges, and animal manures (EPRI 1995b). For our production budget, we assume that the willow crop will be fertilized and provided with additional water through the application of cost-free wastewater from local food-processing plants.

Productivity varies with soil fertility, but 16.8 dry Mg $ha^{-1}$ $yr^{-1}$ (7.5 dry tons/acre/year) is a realistic expectation for the first crop (EPRI 1995b). Yields in the second rotation may be somewhat higher than the first crop. Research on woody biomass production (poplar hybrid) found that initial yields were 20–40% lower than the second coppice rotation (Strauss and Wright 1990). Extensive trials have found the clone SV1 to be the most productive. SV1, planted at 6200 trees/acre on three year rotations with fertilization and irrigation, has yielded 10.0 dry tons of biomass per acre per year (EPRI 1995b). Recent willow breeding projects in Sweden have produced clones expected to have a 20% greater growth potential than those currently used (EPRI 1995b). Our production model used an annual yield of 6 dry tons per acre in the first rotation and 8 dry tons per acre in the following years. This production level is assumed to be achievable with the use of food-processing sludges as supplemental nutrient and water sources.

To model the costs and returns of dedicated energy crop production in northern Indiana, a production budget was assembled (table 1). All activities have been calculated with 1996 Indiana custom equipment rates (Doster 1996). When custom rates were unknown, the values from the 1995 EPRI study "Economic Development through Biomass Systems Integration" were used. These values included all harvest and transportation figures and are expressed in constant 1994 dollars. Some equipment substitution was used to replace equipment primarily found in New York orchards to farm machinery commonly fond on Midwestern farms. Tractor-mounted or pulled sprayers replaced mist blowers and truck spray booms for insecticide and herbicide applications.

Transportation costs add to the total cost of providing biomass to the power plant. As with wood waste, some reprocessing of the wood may be necessary at the power plant to meet the chip size requirement for optimal burning. This reprocessing will entail additional expenses.

## Rate of Return

Encouraging farmers to dedicate portions of their farm to willow production will necessitate proving that the crop will provide the farmers with a reasonable rate of return on their investment. The average return on farm equity in production agriculture over the past four years has been around 5.1% (University of Illinois 1997). *Salix* production pro-

**Table 1. 22-Year Production Budget for Willow in Indiana**

| Activity | #/acre | Cost/Unit | Total Project Cost |
|---|---|---|---|
| Site Prep | | | |
| Mowing | 1.00 | $8.85[1] | $8.85 |
| Herbicide Roundup | 2.00 | $12.30 | $24.60 |
| Tractor applicator | 1.00 | $4.09[1] | $4.09 |
| Plowing | 1.00 | $10.63[1] | $10.63 |
| Disking | 1.00 | $7.48[1] | $7.48 |
| Herbicide Goal | 2.00 | $4.83 | $9.65 |
| Tractor applicator | 1.00 | $4.09[1] | $4.09 |
| Additional requirements | 1.00 | N/A | N/A |
| Planting | | | |
| Cuttings | 6,200 | $0.10 | $620.00 |
| Planting Service | 1.00 | $10.96 | $10.96 |
| Cutback | | | |
| Service | 1.00 | $8.00 | $8.00 |
| Fertilization | | | |
| Year 2, 5, 8, 11, 14, 17, 20 | | N/A | N/A |
| Insecticide Application—as needed | | | |
| Materials Malathion | 1.00 | $0.87 | $0.87 |
| Service | 1.00 | $4.09[1] | $4.09 |
| Sup. Weed Control—as needed | | | |
| Herbicide Roundup | 0.50 | $12.30 | $6.15 |
| Tractor application | 1.00 | $4.09[1] | $4.09 |
| Annual Costs | | | |
| Rent | 1.00 | $40.00[2] | $880.00 |
| Harvesting and Processing Costs | | | |
| Year 4, 7, 10, 13, 16, 19, 22 | | | |
| Harvester Service | 1.00 | $44.52 | $311.64 |
| Field Transport | 1.00 | $8.00 | $56.00 |
| Total Cost per Acre | 1.00 | | $1,971.19 |
| Fuel Price per Ton | 1.00 | | $12.17 |
| Price $/MBtu | 1.00 | | $0.72* |

Sources: EPRI report "Economic Development through Biomass Systems Integration"; 1)Dr. D.H. Doster, Purdue University; 2)Dr. Julian Aktinson, Purdue University; *bone dry wood.

vides the farmer with two sources of income. The first is the sale of the woody biomass in seven separate harvests over 22 years. The second is a one-time sale of cuttings that are severed from the tree roots in the winter after the first year of growth to promote multiple stems.

As seen in our production budget, willows produce 18 tons of biomass at the first harvest of 24 tons of biomass in the next six harvests, or a total of 162 tons of biomass. At a price of $14.00/ton the internal rate of return (IRR) was about 7%. The net present value of the project with 3% discounting was $259.83.

This income level assumes that the farmer collected the cuttings for $0.05 apiece and sold them for $0.10. The farmer kept half of the cuttings from each acre to plant additional land and sold the rest. For an acre with 6,200 trees planted on it, about 12,400 cuttings will be produced. The value of the cuttings that are kept for planting stock was about $620. The income from selling the other half of the cuttings was $620 less the cost of collection, or $310. Total costs and revenues for the 22-year production cycle are presented in table 2.

## Wood Residue

A second way to provide biomass to the power plant is with local wood residues. Haase, Quinn, and Whittier (1994) assessed waste wood resources for Indiana in a report written for NIPSCO entitled "Urban Wood Waste Resource Assessment, the State of Indiana." Based on fuel characteristics, they combined six wood residue groups into three categories by heating value. These cat-

**Table 2. Income from Salix Production**

| | | |
|---|---|---|
| Sale of Crop | 162 tons @ $14.00/ton | $2,268.00 |
| Sale of Cuttings | 6,200 @ $0.05 each | $310.00 |
| Total Revenue | | $2,578.00 |
| Total Cost | | $(1,971.19) |
| Net Profit | | $606.81 |
| Internal Rate of Return | | 0.070 |
| Income Sensitivity | | |
| Net Present Value, 3% | | $259.83 |
| Net Present Value, 7% | | $1.71 |
| Net Present Value, 10% | | $(108.42) |

Source: Sara Nienow 1998.

egories are: urban tree residues, construction and demolition waste (F1); primary and secondary wood processing waste, wood pallet manufacturing and recycling waste (F2); Railroad ties (F3). The heating values of F1, F2, and F3 resources are 8.99 MBtu/ton, 10.73 MBtu/ton, and 16.12 MBtu/ton, respectively. In comparison, blended coal used at the power plant in Michigan City has a heat content of 20 MBtu/ton and willow tree combustion produces about 16.8 MBtu/dry ton.

Although F1 wastes account for 55% of the total available resources in Indiana, they are not recommended for combustion because of the irregular particle sizes and dimensions, a high moisture content (50% or higher) and foreign materials mixed in with the wood (Haase et al. 1995). The supply of F1 wastes is also affected by season and housing starts and demolition activity. F3 wood wastes are not desirable for utilities because the wood is contaminated with toxic chemicals (Foster Wheeler 1996).

This leaves only the F2 category, which consists of primary and secondary wood processing residues, recycled materials, and wood pallet manufacturers. The processes that generate these residues produce a fuel with uniform physical and chemical characteristics: a fuel that is ideal for co-firing. These wastes have a moisture content around 35%. Among these materials, however, there are several competing uses. These uses include mulch, animal bedding, and compost (Haase et al. 1995). Of processing wastes, Foster Wheeler (1996) estimates that 85% of primary and 65% of secondary wastes are currently being consumed.

The widespread distribution of wood wastes makes collection expensive and time-consuming. Therefore, only wood located within 155 miles from Michigan City was considered. A transportation cost formula expresses the ownership and operation costs of trucks used to haul wood wastes.[1] To derive the transportation cost in tons, a 20-ton truckload of wood waste with a 35% moisture content was used in this model. The purchasing cost to obtain these wood wastes depends on the quality of the wood and its competing uses. The base model used a purchase price of $2.00 per ton of wood waste. This cost could vary depending on the alternative uses for waste wood. The transportation cost plus the purchase costs are the total cost of providing wood wastes to the power plant. Reprocessing the wood may be necessary and this would raise costs.

## The Fuel Choice Model

To assess the feasibility of dedicated biomass crops as a fuel, a model must be constructed to determine the optimal mix of traditional and alternative fuels given different regulatory, fiscal, and operating constraints. The model outcome, an optimal fuel mix, is only a function of the input data provided, and these conditions are in constant flux. Thus, the model serves as a guide for purchasing fuels under different scenarios. The fuel choice model, presented in Appendix A, is designed to produce the required amount of electricity at minimum cost subject to heat constraints, environmental regulations, and process constraints. The cost being studied is the total variable cost of burning fuel in the power plant. It includes yearly expenditures on fuel, pollution permits, and ash disposal and is measured in millions of dollars per year. Co-firing capital costs, like equipment to prepare the wood for burning and incremental labor are excluded from this model. These costs, however, are an important component in determining the profitability of co-firing and must be considered outside the model.

There are four fuel types that will be considered: low-sulfur (PRB) coal, high-sulfur (Shoshone) coal, F2 wood wastes, and plantation-produced *Salix*. Each fuel has different physical characteristics including heat value, carbon content, and moisture level (table 3). While the purchase price for wood fuels is higher than coal, lower disposal costs and less $SO_2$ production may make them cost competitive (table 4).

**Table 3. Fuel Types and Characteristics**

| Fuel (miles) | MBtu/ton | $SO_2$ content tons/MBtu | % Ash by weight |
|---|---|---|---|
| Low-sulfur coal | 17.2[1] | 0.00044[1] | 5.38[1] |
| High-sulfur coal | 20.95[1] | 0.00058[1] | 5.48[1] |
| Waste wood (25) | 15.3[3] | 0.00003[4] | 0.7[3] |
| Waste wood (44) | 15.3[3] | 0.00003[4] | 0.7[3] |
| Waste wood (113) | 15.3[3] | 0.00003[4] | 0.7[3] |
| Waste wood (155) | 15.3[3] | 0.00003[4] | 0.7[3] |
| Willow (10) | 16.8[2] | 0.00003[4] | 1.5[4] |
| Willow (30) | 16.8[2] | 0.00003[4] | 1.5[4] |
| Willow (50) | 16.8[2] | 0.00003[4] | 1.5[4] |

NOTE: Moisture content of wood waste is 10%; Willow heat content is for bone dry wood.
Sources: 1)Foster Wheeler 1997; 2)Volk 1997b; 3)Foster Wheeler 1996; 4)EPRI 1995a.

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[1] A transportation formula developed at the University of Tennessee, Knoxville (Foster Wheeler 1996) shows that the cost for wood residues is:
Cost = $35 + ($2/mile)(distance in miles) = $/truckload

**Table 4. Fuel Quantity and Price**

| Fuel (miles) | Quantity in tons | Price per ton |
|---|---|---|
| Low-sulfur Coal | Unlimited | \$21.00* |
| High-sulfur Coal | Unlimited | \$36.67* |
| Wood Waste (25) | 8,040 | \$6.25 |
| Wood Waste (44) | 24,248 | \$8.15 |
| Wood Waste (113) | 22,901 | \$15.05 |
| Wood Waste (155) | 72,803 | \$19.25 |
| Willow (10) | 4,001 | \$15.97 |
| Willow (30) | 25,650 | \$19.91 |
| Willow (50) | 69,601 | \$23.85 |

Source: Sara Nienow 1998; *Bill Williams, NIPSCO Fuel Supply Department.

## Model Restriction

The model has two restrictions on $SO_2$ emissions. The first is that the level of pollution emitted at any time cannot exceed the Clean Air Act Amendments of 1990 standard for non-attainment areas, which is 1.2 lb. $SO_2$/MBtu of fuel burned. The other limits the amount of total $SO_2$ produced in a year to an equal number of $SO_2$ pollution permits. The power plant was issued 17,317 $SO_2$ pollution permits in 1998. The upper boundary was set at 50,000 reflecting the power company's ability to reallocate permits from other facilities and to buy additional permits. If fewer permits are used, the plant can sell them for an income of \$68.14 per permit or bank them for future use.

Other restrictions placed on the model are process constraints. The Powder River Basin (low-sulfur) coal and Shoshone (high-sulfur) coal are blended together in a 60/40 ratio to limit $SO_2$ and $NO_x$ emissions. The amount of wood that can be burned is restricted to 5% by heat content and 10% by weight. This is done to prevent alkali slagging in the system (EPRI 1995b). The total amount of heat produced is fixed at 29,565,000 MBtu. The quantity of each fuel used is restricted by the supply of fuel available. Fuel supply, actual amount of fuel used, and the number of pollution permits consumed were restricted to non-negative numbers. Although the supply of coal is unlimited, an upper boundary of two million tons was set on each coal type to provide the model with bounds. Upper limits of 500 thousand tons were added to wood waste and willow supplies to further limit the model.

## Coal-only and Wood-burning Scenarios

The base model considered only coal fuels. The base model operating results are as follows. The minimized variable cost was \$43,029,700. There were 14,865 $SO_2$ permits used; almost 3,000 permits under the 1998 allowance. This result reflects NIPSCO's strategy of banking as many pollution permits as possible for future use. Low-sulfur coal use was 948,610 tons and high-sulfur coal use was 632,406 tons.

A second scenario was used to evaluate the profitability of woody biomass. With the introduction of biomass co-firing options, variable cost declined to \$42,179,000. The number of pollution permits was reduced to 14,165, about 700 fewer permits than in the base model. In addition to 901,179 tons of low-sulfur coal and 600,786 tons of high-sulfur coal, 75,888 tons of waste wood and 18,878 tons of willow were burned. At this level of co-firing, the model was restricted from using more wood by the heat content constraint that restricts the heat content provided by wood to less than 5% of the total. The average cost of fuel was \$1.22/MBtu for low-sulfur coal, \$1.75/MBtu for high-sulfur coal, \$0.85/MBtu for waste wood and \$1.15/MBtu for willow.

Depending on the alternative uses for waste wood in this area, the power plant may have to pay a premium for wood waste and this case also was considered. When waste wood prices were increased from \$2.00 per ton to \$15.00 per ton, there was increased substitution of *Salix* for wood wastes. The amount of willow used increased to 51,225 tons and the amount of wood wastes used declined to 32,288 tons. Variable cost was \$42,811,204 and the number of pollution permits used was 14,223.

A fourth model tested profitability when willow was the only material available for co-firing. In this case, the variable cost increased to \$42,881,100 and the number of pollution permits needed rose to 14,456. There were 51,225 tons of willow combusted. Instead of being constricted by the heat content constraint, the model was restricted from more co-firing by a lack of wood.

Since the biomass industry is so new, it is assumed that the cost of producing willow will decrease substantially in the future. The greatest areas for cost reduction are in harvesting and chipping operations and in increased crop yield (EPRI 1995b; Hughes and Wiltsee 1997). When the willow yield was increased to 10 dry tons/acre/year for a total of 210 tons of biomass over the 22-year project, the production cost declined from \$12.17 per ton to \$10.56 per ton. This yield increase led to a greater amount of *Salix* being co-fired and co-firing with either \$2.00/ton or \$15.00/ton wood wastes became profitable. Even with a higher yield, co-firing willow alone was still not cost-effective.

If co-firing occurs there are additional capital costs to consider. These include additional equipment for reprocessing, storing, and handling the wood, extra labor, annual maintenance costs, and taxes and insurance charges. Foster Wheeler (1996) estimated the capital cost expenditure at $1,163,000. The additional labor would be $50,000 per year, the maintenance cost would be 5% of the total annualized capital cost ($58,150), and the taxes and insurance would be 2% of the annualized capital cost ($23,260). With a project life of 22 years and an interest rate of 6%, the annualized capital cost would be $96,582. The labor, maintenance, and tax and insurance charges would raise yearly expenses to $227,992. Additional covered storage space to allow for drying green wood down to a moisture content below 25% would require higher capital costs for farmers or the power plant and would vary with the types of harvest and storage systems implemented.

The results of the six scenarios examined are presented in table 5. When waste wood and willow were co-fired in the model, the total variable costs were $850,700 less than the cost of burning coal alone. This indicates that it is profitable for the power plant to co-fire wood wastes with willow and save $622,708 annually (after capital costs are excluded and assuming a waste wood purchase price of $2.00). Co-firing willow without wood wastes or co-firing willow with $15.00/ton wood waste was not profitable and annual variable cost increased.

When the willow yield was increased to 10 dry tons/year, co-firing with either $2.00/ton or $15.00/ton waste wood was profitable. With $2.00/ton waste wood, variable cost is $863,169 less than under the coal-only conditions. Removing the capital costs left a $635,177 reduction in operating costs. When waste wood was $15.00/ton, variable costs were $258,335 less than under the coal-only case. After capital costs were excluded, variable-operating cost declined by $30,343. Co-firing 5% of the plant's yearly heat input would consume 88,000 dry tons of willow. Assuming a 10% combined crop harvest and storage loss, this would require 13,150 acres of land in willow production. This is nearly twice the estimated available acreage.

Since woody biomass is a renewable resource that consumes carbon dioxide during its growth cycle, its use for energy production contributes no net carbon dioxide to the atmosphere when the biomass is produced and consumed as a part of a dedicated energy plantation/energy production system (Mutanen 1993). An energy plantation may even generate positive net sequestration of carbon because continual tree regeneration utilizes more carbon than fully developed trees. Estimates of the value of carbon dioxide ($CO_2$) abatement range considerably from $13.60 per ton Foster Wheeler (1996) to $100 per ton (IUCC 1993). The ultimate value of biomass co-firing may be the ability to reduce $CO_2$ emissions from fossil fuel combustion at a lower cost ($5.00 per ton of reduction compared to $50–$100 with direct emission controls) than other reduction options (Moore 1996). At the Kyoto summit, the Clinton Administration advocated a worldwide system of tradable permits for carbon dioxide emissions. With such a system in place, U.S. electric utilities with good environmental technology would be able to sell emissions permits to less efficient plants or to earn permits by cleaning up inefficient generating plants in developing countries (Coy 1997).

## Concluding Remarks

Co-firing with biomass is currently not cost competitive with coal or natural gas alternatives. Bio-

**Table 5. Fuel Choice Model Results**

| Model | Variable Cost of Electricity Production | Variable Cost Difference from Coal-only Model | Number of $SO_2$ Permits Used | Tons of Willow Co-fired | Tons of Waste Wood Co-fired |
|---|---|---|---|---|---|
| Coal Only | $43,029,700 | — | 14,865 | — | — |
| Willow with $2.00/ton Waste Wood | $42,178,958 | –$635,177 | 14,165 | 18,878 tons | 75,888 tons |
| Willow with $15.00/ton Waste Wood | $42,811,204 | +$9,496 | 14,223 | 51,288 tons | 32,288 tons |
| Willow without Waste Wood | $42,881,059 | +$79,351 | 14,456 | 51,225 tons | — |
| High Yield Willow with $2.00/ton Waste Wood | $42,166,531 | –$635,771 | 14,165 | 25,651 tons | 68,451 tons |
| High Yield Willow with $15.00/ton Waste Wood | $42,771,365 | –$30,343 | 14,165 | 58,586 tons | 32,288 tons |

Source: Sara Nienow 1998.

mass fuel costs for selected DOE programs range between \$1.35 and \$2.56 per million Btu. Electric utilities are able to purchase natural gas for \$1.25 to \$2.25 per million Btu, and coal costs \$0.90 to \$1.35 per million Btu (Moore 1996). Yet our model indicates that co-firing woody biomass at the Michigan City power plant is a financially viable method to reduce the number of pollution permits needed, to lower air emissions, and to lower variable operating costs.

Co-firing biomass for electricity generation is being used by only a handful of power plants in the United States. The lack of adoption has been primarily due to the low cost of traditional fuels over the last decade (Moore 1996). However, the reductions in greenhouse gas emissions agreed to at Kyoto, Japan in December 1997 and the onset of Phase II in the EPA's Acid Rain Program, which will introduce tighter emission standards for $SO_2$, each have the potential to substantially increase the cost of electricity production.

The Energy Information Administration (EIA) has estimated that with the adoption of the Kyoto Protocol the price of coal will rise between 153 and 800% in 2010 and that coal use will decline by between 18 and 77%, particularly for electricity generation (EIA 1998). EIA also estimates that renewable fuels could supply 11 to 22% of the electricity generation market by 2020 as more technologies become economic compared to higher fossil fuel prices (EIA 1998). In addition, there are indirect advantages that can make current co-firing more cost effective. Attaching a value to $CO_2$ pollution, reductions in the delivered price of biomass, higher $SO_2$ permit prices, state and federal mandates, or the ability to charge a premium to consumers for green energy could make co-firing an attractive option for electric utilities.

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# Appendix A

The Fuel Choice Model is designed to produce the required amount of electricity at a minimal cost subject to environmental regulations, process constraints, and fuel prices. The cost being studied is the total variable cost of burning fuel in the power plant. It is comprised of the yearly expenditures of fuel, pollution permits, and ash disposal. It is measured in millions of dollars per year. The objective of the model is to minimize the variable cost while maintaining pollution standards and fuel blending criteria.

| | |
|---|---|
| Project life | 22 years |
| Salvage value | none |
| Unit capacity | 469 MW |
| Capacity factor | 75% |

| | |
|---|---|
| i | Supply levels 1 . . . 4 |
| j | Fuel types: Low-sulfur Coal, High-sulfur Coal, Wood Waste, Willow |
| c | Coal types: Low-sulfur Coal, High-sulfur Coal (subset of j) |
| l | Low-sulfur Coal (subset of j and c) |
| w | Wood Waste and Willow (subset of j) |
| $S_{ij}$ | Supply of fuel j at level i (thousands of tons) |
| $X_{ij}$ | Amount of j fuel at level i (thousands of tons) |
| $C_{ij}$ | Cost of j fuel at level i ($/ton) |
| Pg | Number of pollution permits issues to power plant (17,317) |
| Pu | Number of pollution permits used by power plant |
| PP | Open market price of pollution permits ($68.14/permit) |
| Pa | Total number of permits available to power plant (200,000) |
| D | Disposal cost of ash $1 ($/ton) |
| $A_j$ | Quantity of ash produced by fuel type j (tons) |
| $H_j$ | Heat content of fuel j (MBtu/ton) |
| CAP | Total heat input rate 4500 (MBtu/hour) |
| Hr | Total operating hours 6570 (hours/year) |
| $SO_2L$ | Total amount of $SO_2$ allowed by law 0.0011 (tons/MBtu) |
| $SO_2X_{ij}$ | Sulfur dioxide content of fuel j (tons/MBtu) |
| $So_2T$ | Tons of sulfur dioxide per permit (1) |

Minimize cost =

$$\sum_i \sum_j X_{ij}C_{ij} + (Pg - Pu)PP + \sum_i \sum_j DA_{ij}$$

Subject to:

The first constraint requires the sum of all fuel types to generate a specified level of heat.

$$\sum_i \sum_j X_{ij}H_j = CAPHr$$

The second constraint limits the total amount of $SO_2$ at any given time to be under the federal limit of 1.2 lbs. per MBtu.

$$\sum_i \sum_j SO_2X_{ij}H_j \leq SO_2L$$

This constraint limits the annual amount of $SO_2$ produced to at or under the total number of pollution permits granted to the power plant.

$$\sum_i \sum_j SO_2X_{ij}H_j \leq SO_2TPa$$

The following constraint limits the amount of heat produced by wood to 5 % or less of the total heat produced.

$$\sum_w X_{iw}H_w \leq (0.05)CAPHr$$

The next restriction requires low-sulfur coal to be equal to or greater than 60% of the total amount of coal burned.

$$X_l \geq \sum_c X_{ic}(0.6)$$

This constraint limits the total amount of wood that can be burned to 10% of the total volume of material combusted.

$$\sum_w X_{iw} \leq (0.10)\sum_i \sum_j X_{ij}$$

This restriction requires that the amount of fuel combusted is less than the amount of fuel available at each level.

$$X_{ij} \leq S_{ij}$$

The final restriction specifies that the supply of fuel available, the amount of fuel used, and the number of pollution permits used are all limited to non-negative numbers.

$$X_{ij}, S_{ij}, Pu \geq 0$$